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BOMBARDIER

DUAL-FUEL LOCOMOTIVE PROGRAM

PROGRAM DEFINITION & PRELIMINARY INVESTIGATION

Prepared for
TRANSPORTATION DEVELOPMENT CENTRE
TRANSPORT CANADA

by
ENGINE RESEARCH AND DEVELOPMENT GROUP
RAIL AND DIESEL PRODUCTS DIVISION
BOMBARDIER INC.

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Transportation Development Centre

Transport Canada

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17. Abstract

This report identifies and outlines the technical parameters and activities foreseen as pertinent to the successful demonstration of a Canadian mainline locomotive using natural gas as the main fuel. This document also serves as the preliminary study and phase 1 of the DUAL-FUEL LOCOMOTIVE PROGRAM. The main elements of work identified are: technological literature search and review; dual-fuel conversion package design for the Bombardier model 251 diesel engine using current technology; locomotive modification designs; fuel tender parameters; and, the conceptual design of the power-set, i.e. locomotive and tender. At the completion of the above work (phase 2), the modification of the locomotive, construction of the compressed natural gas tender and the fitting of the converted diesel engine will constitute a dual-fuel locomotive power-set suitable for demonstration. A comprehensive assessment of the limitations of the 251 engine in the dual-fuel mode was also carried out; the findings and recommendations form the basis of subsequent research and development defined as phase 3. The application of the dual-fuel system controls to be investigated in Phase 3 is expected to give the Bombardier locomotive equal power in the diesel and dual-fuel modes. In addition, the requirements and selection of the potential test and demonstration site were made along with expressions of interest from the participants of the program.

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17. Résumé

Ce rapport présente les paramètres techniques à prendre en compte dans la mise en oeuvre d'une locomotive de forte puissance, brûlant surtout du gaz naturel, ainsi que les tâches afférentes à cet objectif. Il constitue également l'étude préliminaire du programme de réalisation d'une locomotive à alimentation mixte, ainsi que l'une des tâches de la phase 1 des travaux. Les tâches prévues sont: recherche documentaire; conception d'un bloc de conversion de technologie courante adaptable au moteur diesel 251 de Bombardier; description des modifications à apporter à la locomotive diesel; définition du tender et, enfin, étude conceptuelle de l'ensemble locomotive-tender. Pour la phase 2, il est prévu de modifier la locomotive diesel, de construire le tender transportant le gaz naturel comprimé et d'installer le bloc de conversion dans la locomotive de manière à approprier celle-ci à l'exploitation expérimentale prévue. Une évaluation exhaustive a été faite des performances du moteur modèle 251 fonctionnant en mode mixte; les résultats serviront de point de départ aux travaux prévus dans la phase 3, qui visent à obtenir de la locomotive équipée du moteur à alimentation mixte les mêmes performances qu'avec du diesel pur. Enfin, le choix du site approprié à l'exploitation expérimentale a été fait et la promesse de participation financière obtenue de la part des secteurs privé et public.

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SUMMARY

Diesel fuel is the major locomotive fuel in Canada and the rest of the world. This fuel is projected to be in relative short supply as our conventional petroleum sources are used up and are replaced by imported and synthetic fuels. It is believed that natural gas (NG) will be more abundant and economical than diesel fuel. Other countries have drawn the same conclusion and have started investigative programs.

This program developed from an established policy of the Canadian Government to reduce the dependency on imported oil in the transportation sector and from the interests of other governmental bodies in assessing available fuels for use in large engines as those found in rail and marine transportation.

Transport Canada's report **TP 6880E** "Natural Gas Rail R&D Strategy" sets out a basic strategy to research the possible use of natural gas by diesel locomotives in Canada. It emphasizes the requirement of a comprehensive technical development program by the locomotive manufacturer preceeding demonstration. As a result, Bombardier Rail and Diesel Products Division was contracted by the Transportation Development Centre (TDC) of Transport Canada to prepare a program definition.

It was determined to break down the development into three progressive phases as outlined below:

Phase I - Program Definition

The tasks in this phase consist of:

1. a technological literature search and review
2. the design of a dual-fuel conversion package to suit the Bombardier model 251 diesel engine
3. a description of required locomotive modifications
4. a definition of fuel tender requirements
5. the preparation of a plan which would lead to a successful demonstration, and
6. an outline of dual-fuel engine development, using advanced technology.

From the literature, the main finding was that current dual-fuel engines are capable of producing equal or greater power than straight diesel engines. Only one reference was found pertaining to dual-fuel (DF) locomotives. This paper discusses the Burlington Northern Railway (BNR) conversion of a General Motors locomotive, which is powered by an Electro Motive Division (EMD) 2-stroke engine. This DF locomotive is in coal-haul service. Abstracts of all pertinent papers are included in this report.

The second task in phase 1 was to design a DF conversion package. The approach taken was to bring the old 251 DF components up to date using current technology. This new design includes replacing mechanical linkages with electronic actuators for both fuels, and the control of the air-fuel ratio by wastegating the turbocharger. In addition, a thorough analytical assessment of the potential performance of a 251-12 cylinder engine with the new DF package was made. It was concluded from this work that comparable output should be possible in both modes at full load. However, the lowest notch speed at which the DF mode can be employed without further R&D would be notch 3.

In task 3 the modifications to the locomotive were considered. These changes consist mainly of interfacing NG fuel controls with existing locomotive systems, fitting of gas leakage detectors and alarms, and an engine gas supply system.

Task 4 addresses the fuel tender from the point-of-view of gas capacity and mode of storage. In order to satisfy the diesel energy displaced with NG, and maintain the same range, liquified natural gas (LNG) must be used. A cryogenic tank car, 50 feet in length, can support four main-line locomotives. The design of the tender is not within the scope of this phase of work.

In task 5 the requirements of demonstration were addressed. Discussions were held with potential participants which included representatives of the federal and Ontario provincial governments, the Canadian Gas Association (CGA), gas utilities and owners of dedicated railways. Kidd Creek Mines in Timmins, Ontario, was selected as the test site with the support of ICG Utilities.

The final task in this program definition phase looked at the areas of further development that will improve the efficiency of the Bombardier 251-DF engine. Task 6 produced a work statement of engine development based on recent research findings. A matrix of tests are planned where the influence of temperature, compression ratio, pilot fuel quantity and injection timing on the lean flammability limit will be studied. This work will also include the development of electronic gas admission and pilot injection valves. Another activity will investigate intake air throttling in conjunction with wastegating. All of these components will be under micro-processor control.

Phase 2 - Dual-Fuel Engine Conversion: Current Technology

In this phase, a 251 12-cylinder engine will be converted with equipment of current design. Also, a single cylinder test cell will be prepared to suit the use of natural gas after which preliminary development work will be done.

Phase 2 consists of the following tasks:

- Project management
- Design review
- Test cell equipment procurement
- Diesel procurement and refurbishing
- Engine conversion
- Engine test and optimization
- Dual-fuel development (1-251 BSCRE-DF)
- Documentation and reports.

Four participants have expressed an interest in financially supporting this work as outlined:

- Gas Métropolitain Inc.
- Bombardier Rail and Diesel Products Div.
- Transport Canada
- Ontario Ministry of Energy.

Phase 3 - Engine Development Advanced Technology

In this phase of the program, a BSCRE-DF will be used to develop and test improved equipment for NG combustion, electronic gas and diesel fuel control, in order to achieve the same power output as obtained in diesel operations, with satisfactory efficiency and reliability. This technology will then be transferred to a multi-cylinder engine and optimized. The work in this phase will consist of many iterations and is long term in nature.

The program, as defined in this report, is deemed mandatory and consistent with TP 6880E "Natural Gas Rail R&D Strategy". At the end of phase 2, the 251-12 DF will be suitable for installation into a locomotive for demonstration. The preparation of the locomotive, CNG fuel tender and fueling facility is within the scope of the demonstration, which is pending approval. Furthermore, it is expected that a demonstration agreement will be obtained at an opportune time during phase 3 to show the achievement of the goals set out in this program.

SOMMAIRE

Au Canada, comme à peu près partout dans le monde, la traction ferroviaire s'alimente surtout en combustible diesel. Or, les prévisions concernant ce combustible sont qu'il y aura pénurie à mesure que nos sources habituelles d'approvisionnement en pétrole s'amenuiseront et que les combustibles d'importation et de substitution prendront la relève. À ce moment, le gaz naturel sera plus répandu que le diesel et donc plus économique que ce dernier. Tirant les mêmes conclusions que le Canada, d'autres pays ont entrepris des programmes de recherche dans ce domaine.

Le présent programme découle de la politique établie par le gouvernement canadien, laquelle vise à affranchir le pays du pétrole qu'il doit importer pour son secteur des transports, et il s'inspire également du désir qu'ont les pouvoirs publics de connaître les caractéristiques des combustibles qui pourraient servir à alimenter les moteurs de forte puissance utilisés dans le secteur du transport ferroviaire et maritime.

Le rapport **TP 6880E** de Transports Canada, intitulé: "Natural Gas Rail R&D Strategy" définit la stratégie à la base de la recherche sur la transformation des moteurs diesel de traction ferroviaire en moteurs pouvant utiliser le gaz naturel; il décrit aussi la nécessité d'avoir un programme cohérent de développement à être entrepris par les constructeurs de locomotives, suivi de l'exploitation expérimentale du résultat de leur recherche. Dans cette optique, le Centre de développement des transports, Transports Canada, a confié à la Division des produits ferroviaires et diesel de Bombardier Inc. la tâche de définir le programme en question.

Les responsables ont trouvé qu'il serait approprié de diviser ce programme en trois phases consécutives, comme suit:

Phase 1 - Définition du programme

Les tâches comprises dans cette phase sont les suivantes:

1. recherche documentaire,
2. conception d'un bloc de conversion diesel-gaz naturel adaptable au moteur diesel modèle 251 de Bombardier,
3. description des modifications à apporter à la locomotive diesel,
4. définition du tender,
5. élaboration du programme d'exploitation expérimentale, et
6. définition sommaire du programme de développement du moteur à alimentation mixte faisant appel à une technologie avancée.

La recherche documentaire a démontré que les moteurs à alimentation mixte courants ont une puissance égale ou supérieure à celle des moteurs brûlant du diesel pur. La seule référence aux locomotives à alimentation mixte a concerné la transformation par Burlington Northern Railway d'une locomotive General Motors animée par un moteur à 2 temps Electro Motive Division et utilisée pour le transport de charbon. Dans le rapport se trouvent les résumés de toutes les références les plus importantes.

Pour ce qui est de la deuxième tâche de la phase 1, conception d'un bloc de conversion, l'approche suivie a été de moderniser le moteur modèle 251 à alimentation mixte. Il a fallu pour cela remplacer la tringlerie mécanique par des actionneurs électroniques commandant l'alimentation des deux combustibles et prévoir le réglage du mélange air-combustible par la régulation de la pression de suralimentation. En outre, une évaluation analytique des performances d'un moteur 251 à 12 cylindres et de son bloc de conversion a été faite. Conclusion: à pleine charge, la puissance fournie par les deux types d'alimentation devrait être comparable, mais, pour ce qui est de l'alimentation mixte, le cran de vitesse le plus bas qui pourrait être utilisé dans l'état actuel de la recherche est le cran 3.

Concernant les modifications nécessaires prévues par la tâche 3, il a fallu adapter les commandes de l'alimentation en gaz naturel aux systèmes existants, ajouter des détecteurs et des avertisseurs de fuites de gaz et prévoir un circuit d'alimentation en gaz naturel.

La tâche 4 s'est attaquée à la question du tender sous l'angle de la capacité de stockage et de la forme à adopter pour stocker le combustible. Afin de garder la même autonomie qu'en diesel pur, le gaz naturel devra être utilisé sous la forme liquéfiée. Ainsi, un réservoir cryogénique de 50 pieds de long est en mesure d'alimenter quatre locomotives de forte puissance. Quant au tender lui-même, sa conception n'entre pas dans le cadre de cette phase des travaux.

Au cours de la tâche 5, les besoins relatifs au programme d'exploitation expérimentale ont été abordés avec les principaux intéressés, à savoir le gouvernement fédéral et celui de l'Ontario, l'Association canadienne du gaz, les distributeurs de gaz et les sociétés de chemins de fer concernées. Le choix du site des essais s'est porté sur les mines Kidd Creek à Timmins en Ontario, l'appui nécessaire étant fourni par Intercity Gas.

La tâche 6, qui était celle de la définition du programme de développement du moteur modèle 251 à alimentation mixte et de l'amélioration de ses performances, a débouché sur un énoncé des travaux nécessaires, fondé sur les résultats de recherches récentes. Un plan d'expérimentation a été dressé, comportant des essais visant à déterminer l'influence des paramètres comme la température, le taux de compression, la quantité de combustible d'injection pilote et l'avance à l'injection sur la limite inférieure d'inflammabilité en mélange pauvre.

Il est également prévu d'étudier la possibilité de commander électroniquement l'ouverture et la fermeture des soupapes d'admission du gaz ainsi que l'injection pilote, et celle de combiner le réglage du débit d'air d'admission avec la régulation de la pression de suralimentation. Tous ces éléments seraient commandés par micro-processeur.

Phase 2 - Transformation en moteur à alimentation mixte - technologie courante

Dans cette phase, il est prévu de convertir un moteur modèle 251-12 cylindres au moyen d'éléments de technologie courante, d'élaborer une cellule d'essai monocylindre adaptée au gaz naturel et de lancer les travaux préliminaires menant à la mise au point du moteur.

La phase 2 comporte les tâches suivantes:

- gestion du projet,
- revue conceptuelle,
- achat du matériel nécessaire à la cellule d'essai,
- achat et remise en état du diesel,
- conversion du moteur,
- essai et optimisation du moteur,
- mise au point du moteur à alimentation mixte (1-251-BSCRE-DF),
- compte rendu.

Les quatre participants intéressés à financer ce projet sont:

- Gaz métropolitain Inc.,
- Division des produits ferroviaires et diesel, Bombardier Inc.,
- Transports Canada, et
- Ministère ontarien de l'énergie.

Phase 3 - Mise au point d'un moteur de technologies de pointe

Durant cette troisième phase, le moteur 251 à alimentation mixte servira à la mise au point et à l'essai de technologies avancées dans les domaines de la combustion du gaz naturel et de la chaîne de commande électronique des alimentations diesel et gaz naturel, en vue d'obtenir du moteur à alimentation mixte les mêmes performances qu'avec du diesel pur, et d'atteindre des niveaux de rendement et de fiabilité satisfaisants. Une fois au point, cette technologie pourra être transférée à un moteur multi-cylindres et optimisée. Tous ces travaux nécessiteront de nombreuses itérations et seront forcément de longue haleine.

Comme il est décrit dans le présent rapport, le programme se présente comme une nécessité impérieuse qui s'inscrit dans la stratégie élaborée dans le rapport TP 6880E. Dès la fin de la phase 2, le moteur 251-12 cylindres à alimentation mixte pourra être installé dans une locomotive, aux fins de l'exploitation expérimentale. Les préparatifs concernant la locomotive, le tender d'alimentation en gaz naturel comprimé et les installations d'approvisionnement entrent dans le cadre de l'exploitation expérimentale, dont l'approbation est imminente. Quant à l'entente sur la mise en oeuvre de celle-ci, on espère qu'elle pourra être conclue à temps durant la phase 3 de manière à réaliser tous les objectifs fixés.

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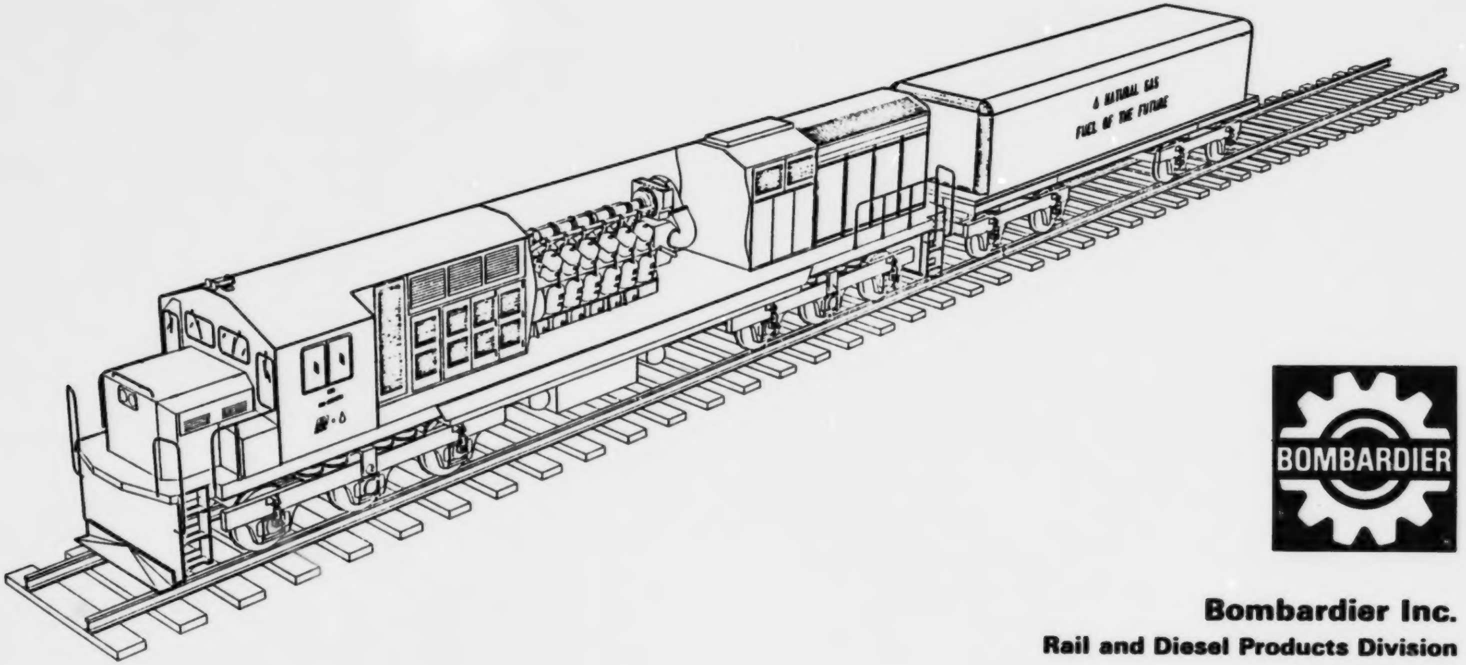
Appendix "A" - Literature Search: - Reviewed Abstracts
Appendix "B" - Lean-Operating Limit for a Dual-Fuel Natural Gas Locomotive
Appendix "C" - Phase II Work Statement: - Engine Conversion (Current Technology)

NOMENCLATURE

ALCO - BOMBARDIER RAIL AND DIESEL PRODUCTS NEW YORK
BCRC - BRITISH COLUMBIA RESEARCH COUNCIL
BNR - BURLINGTON NORTHERN RAILWAY
BRDPD - BOMBARDIER RAIL AND DIESEL PRODUCTS DIVISION
BSCRE - BOMBARDIER SINGLE CYLINDER RESEARCH ENGINE
CGA - CANADIAN GAS ASSOCIATION
CNG - COMPRESSED NATURAL GAS
DF - DUAL-FUEL
DOE - DEPARTMENT OF ENERGY
EMD - ELECTRO MOTIVE DIVISION, GENERAL MOTORS
EMR - ENERGY, MINES AND RESOURCES CANADA
FIE - FUEL INJECTION EQUIPMENT
FRA - FEDERAL RAILROAD ADMINISTRATION (US)
ICG - INTERCITY GAS
GMI - GAZ METROPOLITAIN INC.
KCM - KIDD CREEK MINES
LNG - LIQUIFIED NATURAL GAS
MEny - ONTARIO MINISTRY OF ENERGY
NG - NATURAL GAS
NRC - NATIONAL RESEARCH COUNCIL OF CANADA
OEM - ORIGINAL EQUIPMENT MANUFACTURERS
ONR - ONTARIO NORTHLAND RAILWAY
ORNL - OAK RIDGE NATIONAL LABORATORY
SwRI - SOUTHWEST RESEARCH INSTITUTE
TC - TRANSPORT CANADA
TDC - TRANSPORTATION DEVELOPMENT CENTRE (TRANSPORT CANADA)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Bombardier Inc.
Rail and Diesel Products Division

Engine R & D

BOMBARDIER DUAL–FUEL LOCOMOTIVE POWER SET

INTRODUCTION

The Canadian railway system is approximately 99% dependent on diesel electric locomotives fueled by No.2 diesel oil. Engineering and research concerns, the CGA (representing the gas utilities) and provincial energy ministries used this statistic and the enormous quantities of NG which would be consumed as justification of a NG burning locomotive in ENERDEMO program. (This is an EM&R program which supports the demonstration of energy conserving systems in the transportation sector). In September 1984 a program development meeting was held at BC Research in Vancouver. The meeting emphasized that before a demonstration project could be launched, it must be proceeded by major technical development by the locomotive manufacturer involved and accompanied by operational, economic and regulatory studies. As a result the "NATURAL GAS RAIL RESEARCH & DEVELOPMENT STRATEGY" TP 6880E was commissioned by TC, it sets out a plan of action in which the NG locomotive R&D program is defined.

The dual-fuel locomotive program consists of the following elements:

Phase 1	Program definition Preliminary investigation
Phase 2	Engine conversion - current technology
Phase 3	Engine development - Advanced technology

The phases of work are such that depending on development results GO/NO GO decisions on further developments and demonstrations can be made.

It is well understood that any scheme seeks to utilize NG as a locomotive main fuel must overcome the obstacles which prevented the medium-speed dual-fuel (DF) engines from obtaining comparable performance to the diesel, i.e. no reduction of power output when running on dual-fuel in the past, therefore avoiding the necessity of adding motive power (locomotives).

This report presents the detailed plan leading to the demonstration of a dual-fuel (DF) locomotive with current technology and the work strategy to achieve the objective of a main line-haul locomotive fueled mainly by NG.

2. LITERATURE

As outlined in Phase I work statement, this state-of-the-art review would set the parameters which would be addressed within the projects scope.

The literature search included conversion of medium-speed diesel locomotive engines operating on natural gas, including but not limited to aspects of gaseous fuel combustion, dual-fuel operation, electronic injection and control systems.

Appendix "A" contains abstracts of those publications which were found pertinent. In addition, further references are included as supporting documentation to Appendix "B", "Lean Operating Limit for a Dual-Fuel Natural Gas Locomotive".

The key factors considered were:

- Conversion of Large Engines
- Dual-Fuel Combustion
- Lean Operating Limit of Dual-fuel Engines
- Dual-Fuel vs Diesel Power Output

2.1 Findings of the Literature Review:

Large stationary diesel engines have been converted to run on natural gas for more than forty years. There are approximately fifty NG burning engines available in today's market. Most of these engines are found in co-generation stationary, gas compression and pumping applications. Recently, a number of ocean going vessels have been converted to dual-fuel and a number of engine manufacturers (M.A.N. and Sulzer) have developed a reliable, efficient conversion system with the following benefits:

- Reduced pollution
- Lower power assembly wear
- Fewer oil changes
- Lower maintenance costs.

With respect to railroad application, papers published refer only to Burlington Northern Railway (BNR) and their conversion of an Electro-Motive Division (EMD) powered freight locomotive. It should be noted here that locomotive builders such as EMD (GM) and Bombardier (Alco) produced dual-fuel engines thirty years ago, with, however, lower thermal efficiency than that of their diesel engines.

Advances in combustion fundamental research computer modelling have given a better understanding of the in-cylinder open and close cycle process. Materials and the quality control of products allow for higher forces to be generated. Microprocessor management and diagnostics enable to fine tuning of systems resulting in higher efficiencies. It can also be seen in the literature references that in most cases, higher power outputs can be achieved in the dual-fuel mode than in the diesel mode of operation of small high-speed engines such as those found in heavy duty highway vehicles. Little work has been done or published on medium-speed railroad type engines. Appendix "B" "Lean Operating Limit for A Dual-Fuel Natural Gas Locomotive" also presents an assessment of pertinent literature. At present, both Southwest Research Institute (SwRI) and Ricardo are in the process of completing research projects concerning medium speed diesel engines. SwRI's work pertains to direct injection of NG into a 2-stroke locomotive engine and Ricardo is investigating a spark ignited gas-fired 4-stroke engine. The published reports of these studies will influence this program.

3. PHASE 2 - DUAL-FUEL ENGINES: CURRENT TECHNOLOGY

3.1 Engine Development and Conversion - Background

During the past 25-30 years, many of the obstacles which prevented the dual-fuel engine from obtaining comparable performance to the diesel-fueled version have been overcome.

The Diesel & Gas Turbine Worldwide Catalog,Vol.42 lists 55 O.E.M. offered gas burning engines. Approximately half of the engines offered are in the power range suitable for locomotive application. However, they can only be found in stationary and marine installations.It should also be noted that these engines are presented with equal horsepower ratings.

Bombardier's confidence in the above advances is demonstrated by its decision to produce a spark ignited gas version of the Alco 251 engine. This work began in early 1984. The fundamental changes from diesel to spark ignition are similar to those required for diesel to dual-fuel except where ignition and fuel injection are governed.

Spark ignited (Otto) conversions are suitable for applications where the availability of gas is guaranteed, and full substitution of diesel fuel is an advantage. Disadvantages are more elaborate changes to the engine and complete dependency on availability of NG.

Dual-fuel (pilot-injection) engines utilize a small percentage of diesel fuel solely as an ignition source for the NG. The advantages of this type are, fewer alterations to the diesel engine; retrofittable; large amount of diesel fuel substituted' and emergency return to diesel fuel is still possible. The disadvantage is poorer thermal efficiency at low engine loads and speeds. From these facts, it can be seen why the dual-fuel engine is considered the best approach for the transportation sector and specially for locomotive application.

3.2 Factors Affecting Power Output and Efficiency

The traditional approach to dual-fuel conversion, as exemplified by the Alco and EMD designs of the 1950's, involved superficial modification of the existing diesel engine, by the addition of gas supply piping, gas admission valves, and special control linkages. These changes were such that diesel function was essentially unchanged. When the engine is operating in the gas mode, diesel fuel delivery is limited to a very small quantity, which ignites the air-gas mixture in the cylinder, since gaseous fuels are not self-igniting at the temperatures and pressures achieved in diesel engines. The engine is governed in the gas mode by throttling the gas supply. The control mechanism provides means to adjust the air flow, since the air-fuel ratios burning gas must be maintained within closer limits than when the engine is burning diesel fuel.

Several limitations are imposed by this approach. For example, the fuel cam, the fuel injection pump, and fuel injection nozzle are all optimized for power and efficiency in diesel operation. The exact same system is then asked to deliver 2.3% maximum fuel in a very stable manner such that it will efficiently ignite the change in the cylinder. In fact, the fuel system is too large, and the fuel spray is fundamentally incorrect.

The gas admission valve operated by a linkage from the air intake valve train. This implies that the gas valve can only be operated at the same time as the air intake valve, thereby again limiting the ability to optimize gas admission.This situation becomes more critical at higher power outputs, which require large valve overlaps to increase the cooling air flow through the cylinder, thus increasing the probability in introducing gas into the exhaust manifold.

Control of the air/gas ratio is achieved by pre-set mechanical linkages, which are difficult to adjust, and which have no protection against the effects of varying ambient conditions e.g. air temperature and altitude.

These are only some of the areas requiring development work leading to the design of modern, efficient, dual-fuel engine.

3.3 Current Technology

Bombardier/Alco 251 DF engines ceased production in 1966 due to the increased availability of diesel fuel and the advances in diesel engine technology. In response to a growing domestic and export interest, prompted by the world petroleum situation, Bombardier has commenced research and development to bring the 251 DF engine to the state-of-the-art. The 251 DF work is an extension of the 251-SI. Development studies started in 1984. This is possible since the difference lies mainly in the NG ignition source. Significant improvement was realized due to the optimization of the gas supply and admission system in addition to replacing the mechanical fuel control (linkage and cams)with programmed electro-mechanical actuators (Fig. 3.1)

Today's DF engine requires that comparable performance be achieved in either full diesel mode or in pilot ignited gas mode. In considering that objective, the following must be recognized.

1. Best diesel efficiency is sensitive to:

    a. Fuel injection timing
    b. Fuel injection spray pattern
    c. Fuel injection rate
    d, Turbocharger match
    e. Air: fuel ratio, total and trapped
    f. Compression ratio

2. Best gas efficiency is sensitive to:

    a. Gas admission timing
    b. Gas quality
    c. Gas-air mixture
    d. Pilot fuel timing
    e. Pilot fuel quantity
    f. Turbocharger match
    g. Air: fuel ratio, total and trapped
    h. Compression ratio

3.3.1 Thermal Efficiency

Figure 3.2 shows the relative thermal efficiency values for several different dual-fuel engines operating on natural gas, as a function of rated load. It is seen that the gas-fueled engine approaches and sometimes exceeds the diesel thermal efficiency at 100 percent load. However, as the load is decreased, so does the thermal efficiency of the gas engine.

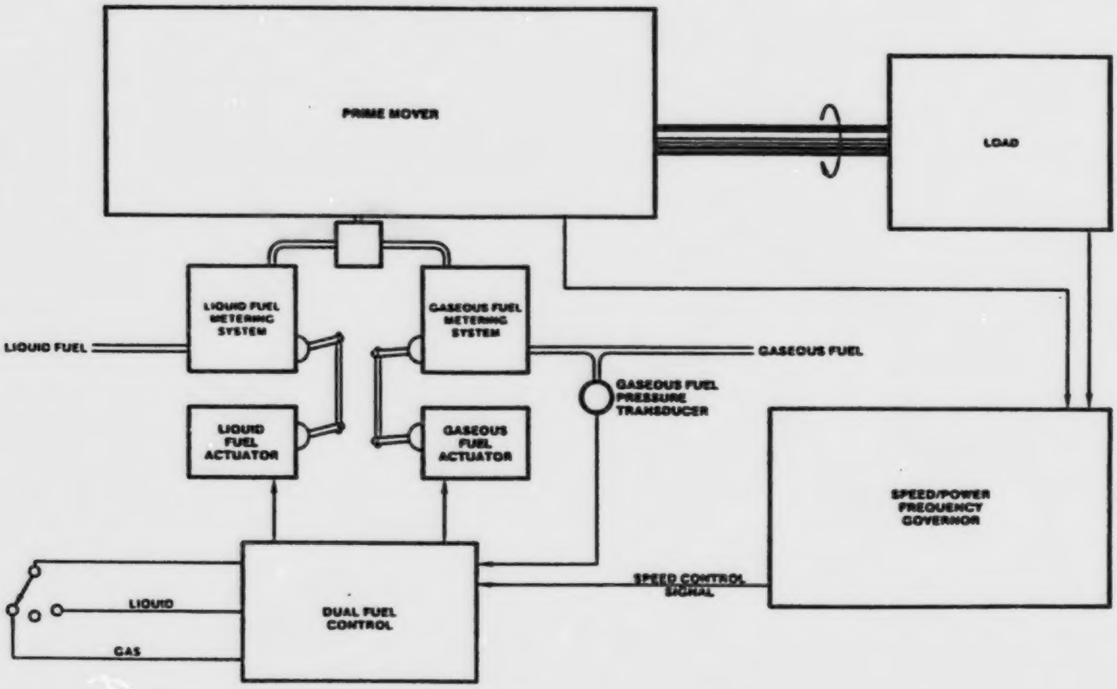

PRIME MOVER
LOAD
LIQUID FUEL METERING SYSTEM
GASEOUS FUEL METERING SYSTEM
LIQUID FUEL
GASEOUS FUEL
GASEOUS FUEL PRESSURE TRANSDUCER
LIQUID FUEL ACTUATOR
GASEOUS FUEL ACTUATOR
SPEED/POWER FREQUENCY GOVERNOR
SPEED CONTROL SIGNAL
LIQUID
GAS
DUAL FUEL CONTROL

FIGURE 3-1 — TYPICAL CONTROL SYSTEM DIAGRAM

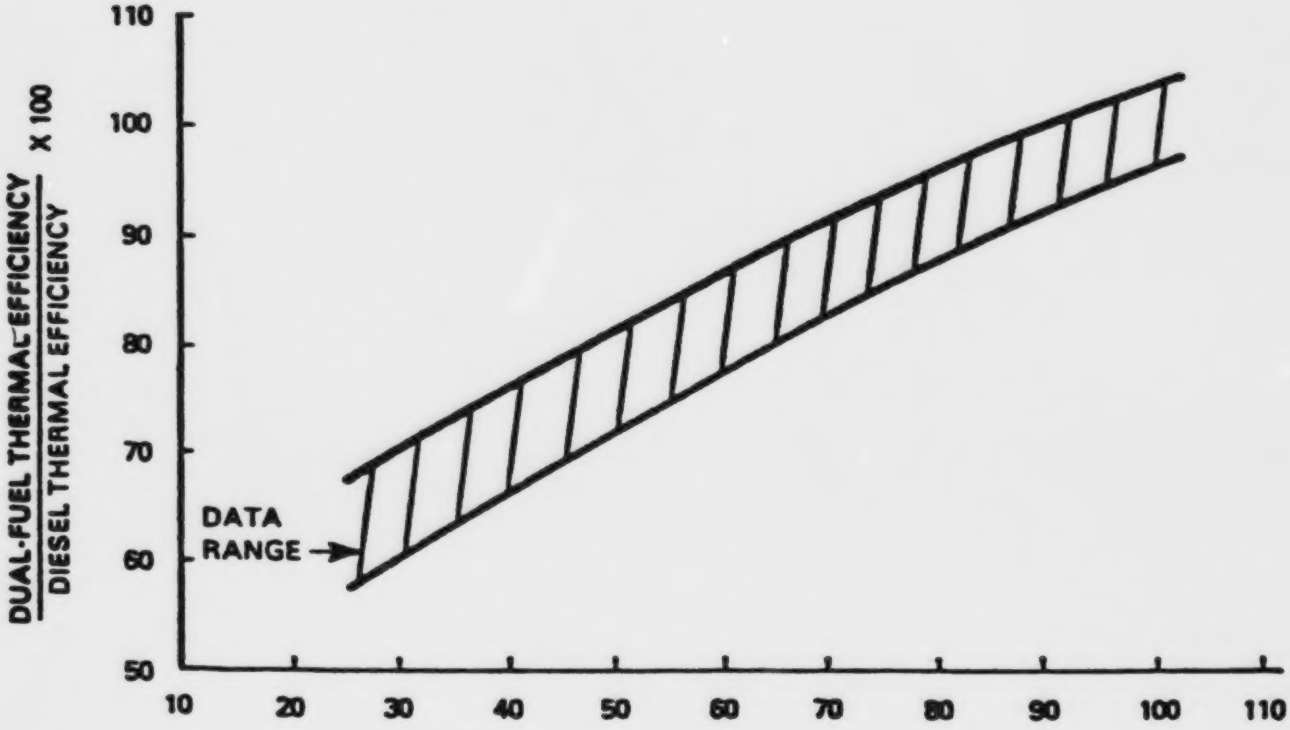


FIGURE 3-2 — DUAL-FUEL THERMAL EFFICIENCY

At lower loads or fuel-air ratios, the flame propagation speed is reduced thereby increasing the time required for burning all the gas and, in turn, reducing the thermal efficiency. If the timing of the pilot fuel is advanced as the engine load or fuel-air ratio is decreased, some improvement will be realized.

The 251 DF engine is able to maintain a high thermal efficiency because the turbocharger is first optimized for low load operation with the excess pressure progressively wasted at higher loads. Also, the programmable electronic governor monitors the engine operation or load and then applies a control signal to one or both of the fuel actuators and the turbocharger waste-gate.

3.3.2 Pilot and Gas Fuel-Air Ratio

The minimizing of the diesel fuel quantity in the gas-fuelled mode is critical. If the pilot quantity is reduced below its optimum value, the lean limit of the fuel-air mixture is raised due to the weaker (pilot) ignition source. Regulating conventional fuel injection equipment (FIE) to deliver small pilot quantities is difficult. The approach being taken is to evaluate injection pumps with a doubler helix. However, a conventional pump calibrated for small delivery is being used until the desired pumps are available.

Below the lean flammability limit fuel-air ratio, the engine will misfire and, on the other hand, the tendency of the engine to knock is increased as the bounded on the top by the knock region and on the bottom by the misfiring region. Figure 3.3 illustrates these limits as a function of compression ratio.

3.3.3 Effects of Compression Ratio

The gas-fueled engine is similar to a spark-ignition engine. The burning of natural gas is by the progression of flame front through the combustion chamber. The pressure and temperature of the unburned gas ahead of the flame increases when the temperature of the unburned gas exceeds a certain limit. It will detonate, causing the engine to knock. A high compression ratio (CR) increases the tendency of the unburned gas to detonate,

When working in the diesel mode, the CR requirements are different. The fuel-air mixture is ignited by the hot compressed air, and a low CR will cause ignition instability and, in some cases, the engine will not start or run.

As can be seen, the requirement for DF engine CRE are conflicting and the design CR must be a compromise. However, this most fundamental parameter when applied to the Bombardier engines is controlled by optimized turbocharging and waste-gating to the limit of its effectiveness.

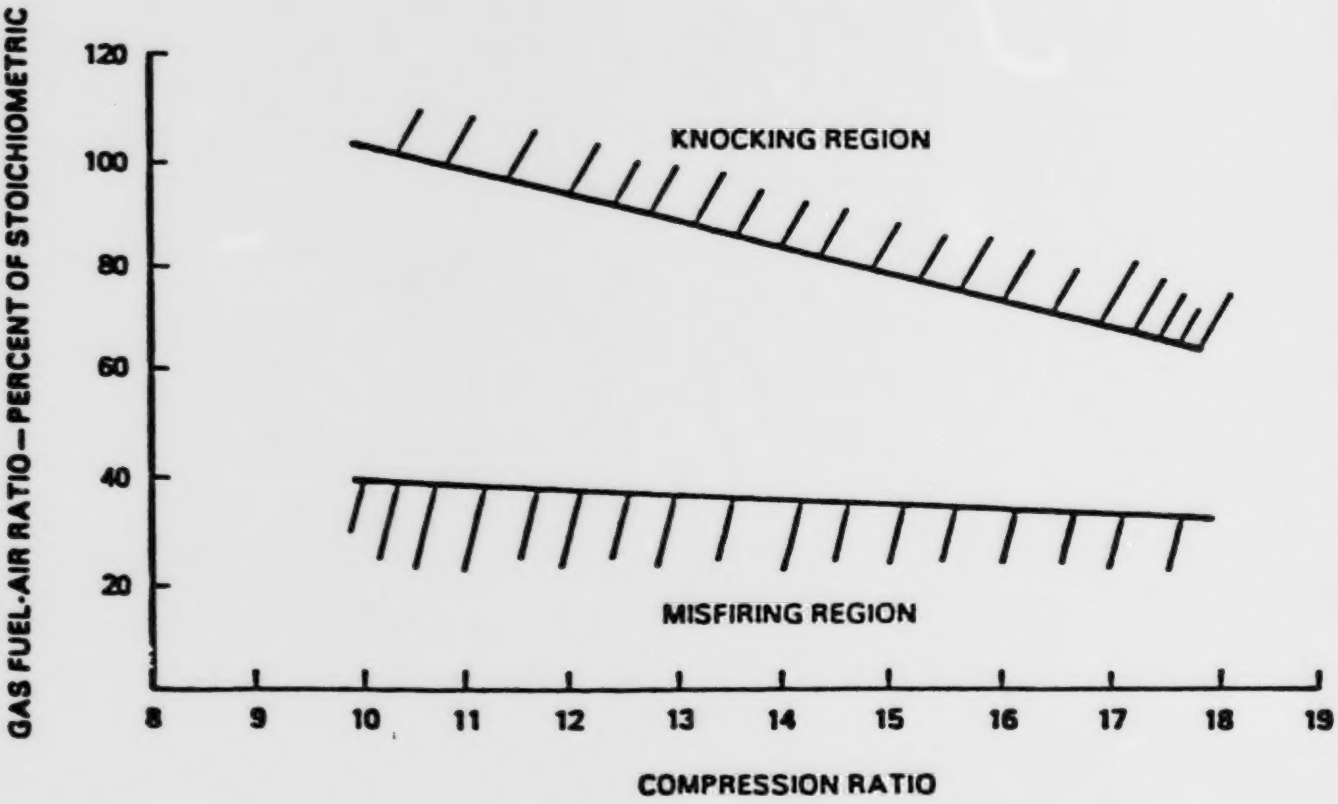


FIGURE 3-3 — GAS FUEL-AIR RATIO EFFECTS

Table 1 shows the targeted ratings for the current 251-DF engines. Based on laboratory observations, these targets are somewhat conservative.

Table 1

251 DF - Basic Ratings

	1000 RPM	1100 RPM	1200 RPM
MODEL	BHP	BHP	BHP
6	1000	1100	1200
8	1335	--	--
12	2000	2200	2400
16	2675	2940	3200
18	3000	3300	3600

3.4 12-Cylinder 251 Dual Fuel Engine

Selected to comply with the Phase II objective of this locomotive demonstration, the engine to be converted is a 12-cylinder 251 C5 engine. After conversion, this engine will be re-designated as a 12-251 C5/DF. Fig. 3.4 shows the DIESEL ENGINE SPECIFICATION SHEET.

EDQ-287

Bombardier Inc.
Rail and Diesel Power Products Division

DIESEL ENGINE SPECIFICATION

Computer reference No. RDE484510-001

Model 12 CYL. 251C5/DF

Engine Order No.

Rating 2200 BHP at 1050 RPM

Customer R&D

Design Altitude MSL

No. of units 1

Compression Ratio 11.5 :1

Pistons MEX HAT

Injection Equipment: Pumps 15 mm

Model FC0AB150A0372

Timing: 25.5° BTC

Max. Rack - mm

Drawing

Nozzle: 9 Holes .325 dia.

Model

Drawing 23B74100-1

Holder Model 72-77310-287

Drawing 23A74099-1

Camshaft Overlap: 140° degrees.

Turbocharger: Type 131

Specification Z105/205A-131-4-A12

Nozzle 20.5 sq. in. 18 deg.

Diffuser 10.5 sq. in. 15 deg.

List QM-26T32495-4

Exhaust Manifold: SINGLE

Pipe, Type WASTEGATED

Aftercooler: Model: YOUNG 28A71538-3

Starting System: ELECTRIC

Governor Model WOODWARD 501 DCS/3199/3199

Generator Model GTA-17PB1

Mounting Foot Height 23.5 inches below crankshaft centreline.

Engine Outline Drawing R94030017

Performance Data NA

Remarks:

Date: 880106

Issued by: M.L.P.

Revision dates:

FIGURE 3-4

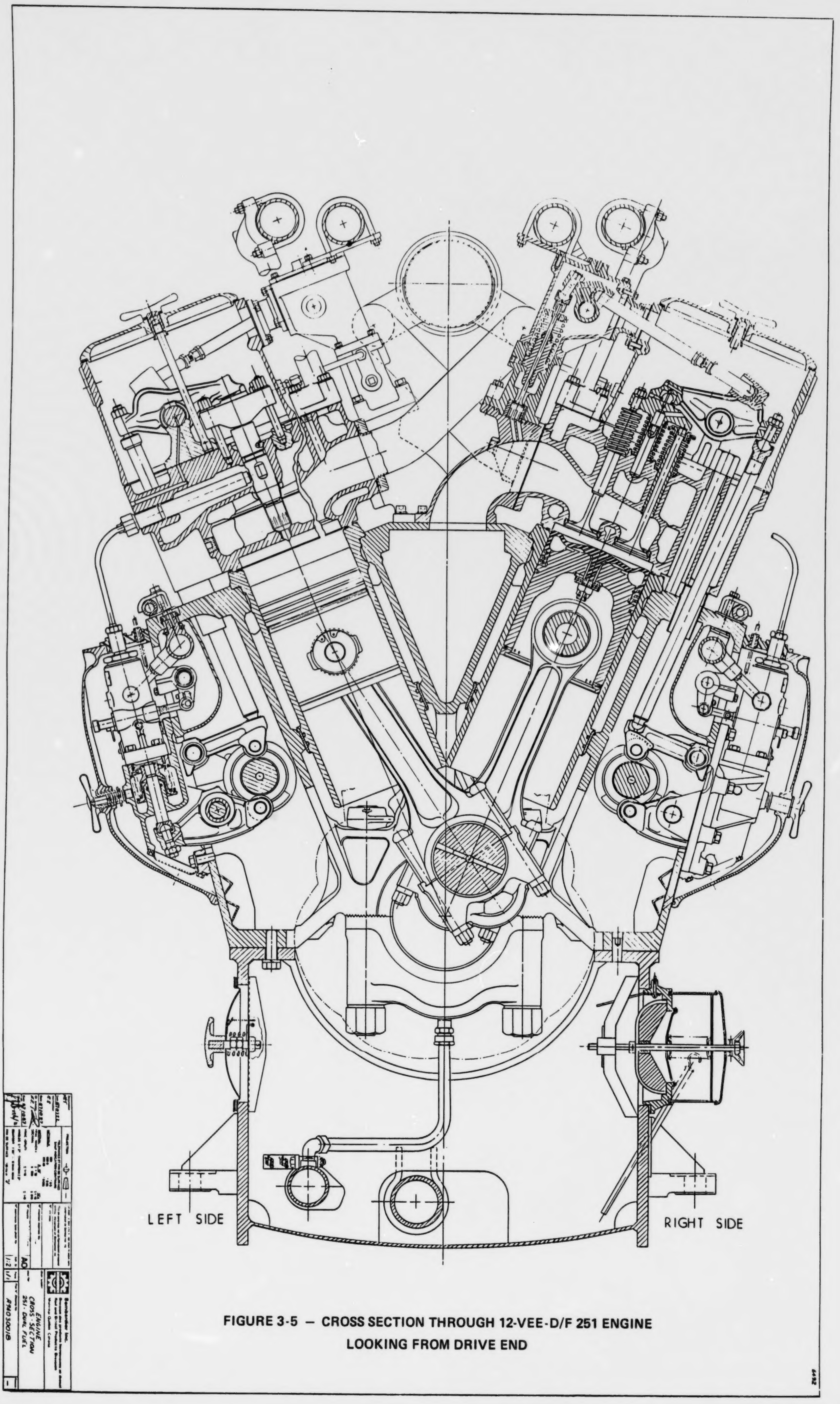

LEFT SIDE
RIGHT SIDE
6492
Bombardier Inc.
ENGINE
CROSS-SECTION
251- DUAL FUEL
AO
1:2
R91030018

FIGURE 3-5 — CROSS SECTION THROUGH 12-VEE-D/F 251 ENGINE
LOOKING FROM DRIVE END

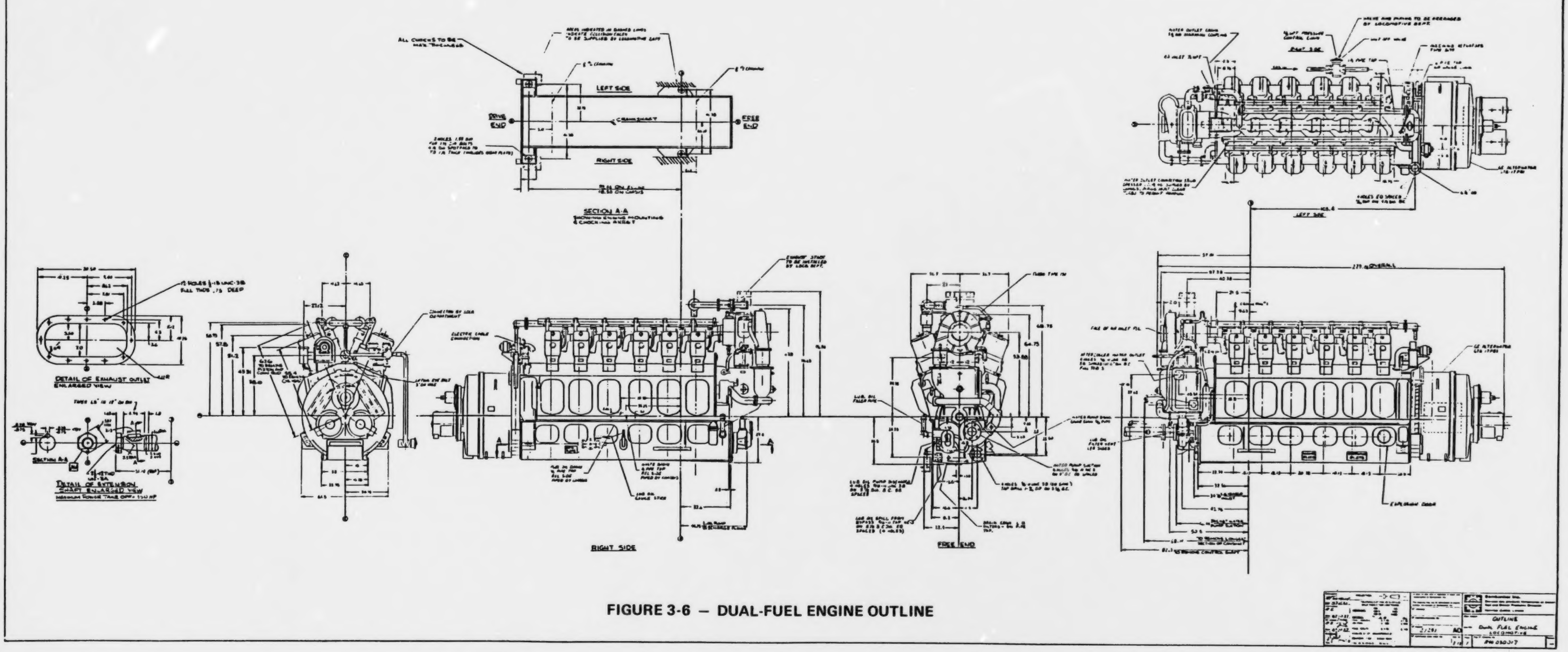
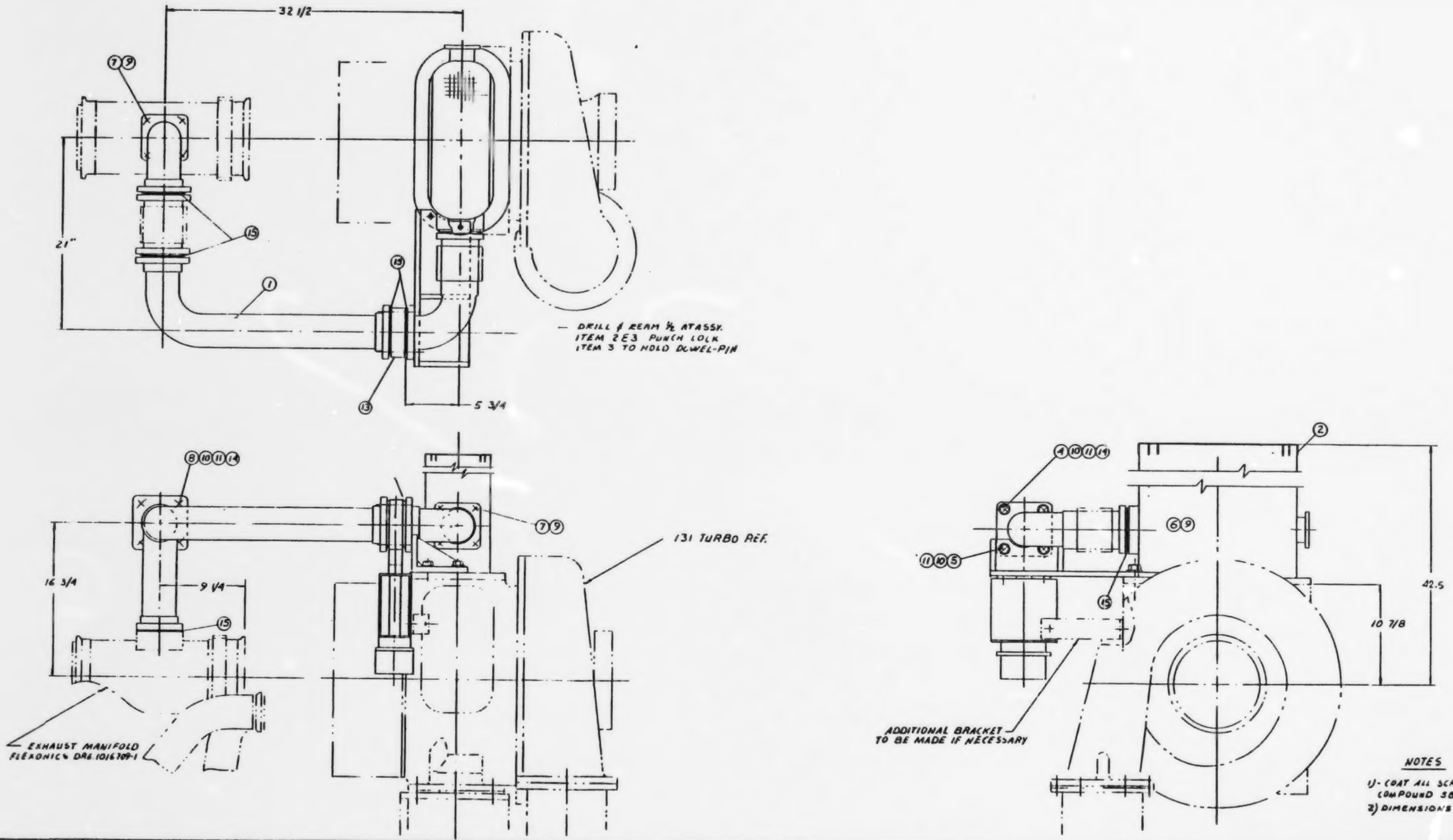

ALL CHOCKS TO BE MAX. THICKNESS
LEFT SIDE
DRIVE END
CRANKSHAFT
FREE END
RIGHT SIDE
SECTION A-A
SHOWING ENGINE MOUNTING & CHOCKING ARR'GT
EXHAUST STUD TO BE INSTALLED BY LOCO. DEPT.
12 HOLES FULL THDS .75 DEEP
DETAIL OF EXHAUST OUTLET ENLARGED VIEW
SECTION A-A
DETAIL OF EXTENSION SHAFT ENLARGED VIEW
ELECTRIC CABLE CONNECTION
RIGHT SIDE
LUB. OIL FILLER PIPE
FREE END
LEFT SIDE
EXPLOSION DOOR
OUTLINE
DUAL FUEL ENGINE
LOCOMOTIVE

FIGURE 3-6 — DUAL-FUEL ENGINE OUTLINE

1		W.G. PIPING		#1016994 FLEXONICS ASSY	1
2	R94026162-004	EXH. ADAPTER			1
3	R94-026091	BRACKET			1
4	2P11931-144	S.S. BOLT		5/8-11 × 4 1/2	2
5	2P11931-128	S.S. BOLT		5/8-11 × 4	2
6	2P11904-040	S.S. BOLT		1/2-13 × 1 1/4	2
7	2P11904-056	S.S. BOLT		1/2-13 × 1 3/4	8
8	2P11931-080	S.S. BOLT		5/8-11 × 2 1/2	8
9	1P83505-018	LOCK WASHER		1/2	10
10	1P83505-020	LOCK WASHER		5/8	8
11	1P60020-020	S.S NUT		5/8-11	8
12					
13	572-058150-006	W.G. VALVE			1
14	1P83006-020	PLAIN WASHER		5/8	12
15	15D76254-1	GASKET			6


32 1/2
⑦⑨
⑮
21"
①
⑮
⑬
5 3/4
DRILL ∅ REAM ½ AT ASSY. ITEM 2 & 3 PUNCH LOCK ITEM 3 TO HOLD DOWEL-PIN
⑧⑩⑪⑭
⑦⑨
131 TURBO REF.
16 3/4
9 1/4
⑮
EXHAUST MANIFOLD FLEXONICS DWG. 1016709-1
②
④⑩⑪⑭
⑥⑨
⑪⑩⑤
⑮
42.5
10 7/8
ADDITIONAL BRACKET TO BE MADE IF NECESSARY

NOTES

1) - COAT ALL SCREWS WITH ANTI-SEIZING COMPOUND 58120-6003

2) DIMENSIONS ARE FOR REF. ONLY.

FIGURE 3-7 — EXHAUST WASTE GATE

Bombardier Inc.
Division des produits ferroviaires et diesel
Rail and Diesel Products Division
Montreal Quebec Canada

WASTE GATE ARRANGEMENT
(131 TURBO- SINGLE PIPE EXH)

251 - D/F
AO
1/4
1
R98025090

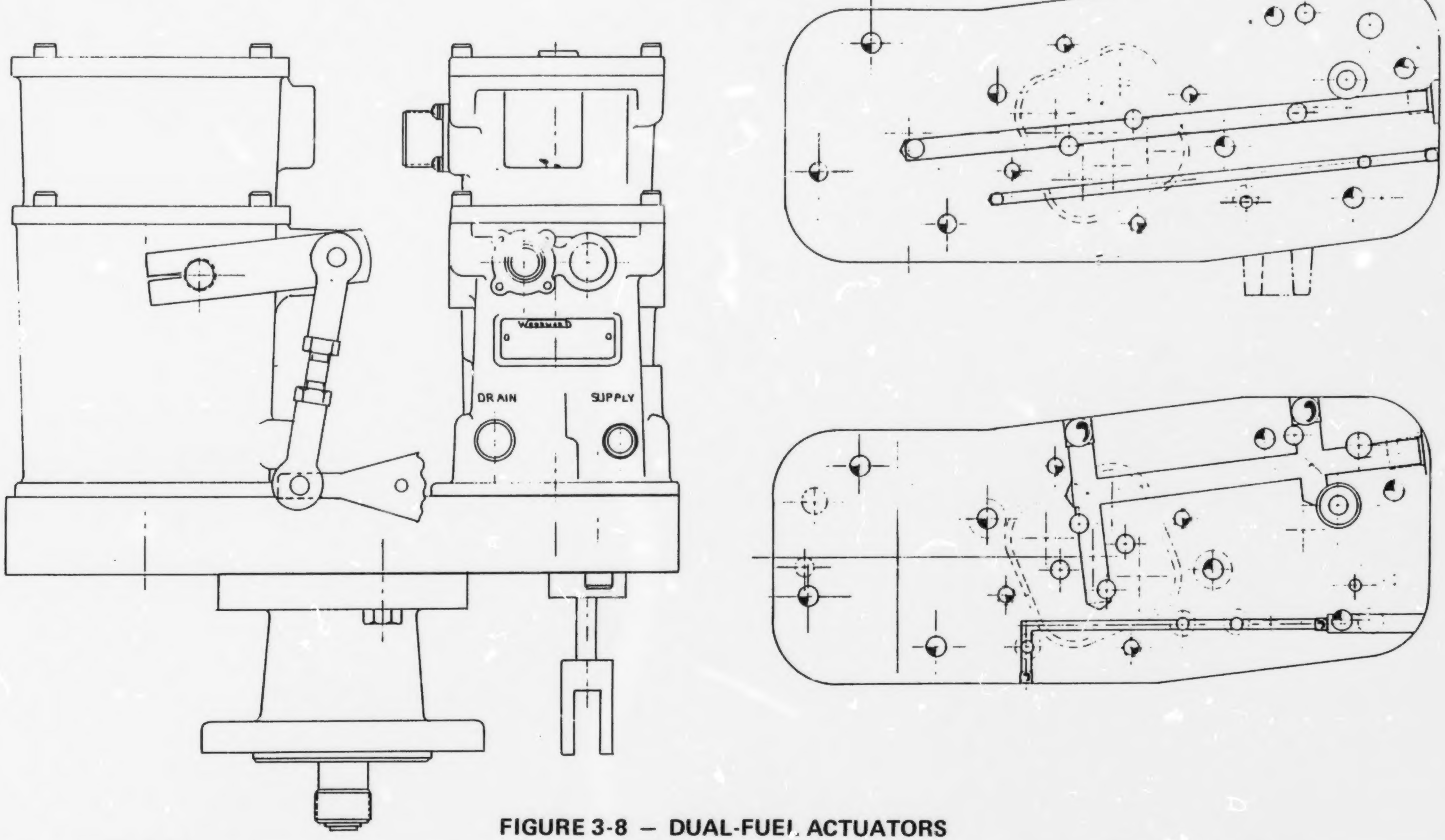


FIGURE 3-8 — DUAL-FUEL ACTUATORS

V. TREMBLAY
R.S.
97 11 05
R.S.
97 11 05

PROJECTION

TOLERANCES ET FINI DE SURFACE
SAUF INDICATION CONTRAIRE

Bombardier Inc.
Division des produits ferroviaires et diesel
Rail and Diesel Products Division
Montreal Quebec Canada

ACTUATORS ASSEMBLY
WOODWARD TYPE #3199

251 DUAL FUEL
A1

4. LOCOMOTIVE

4.1 Operational Consideration

More than 50 percent of all North American Class 1 railroad locomotives have been purchased since 1970. Therefore, any plan which intends to introduce NG as a fuel for locomotives must consider the ability to convert existing units such that: minimal structural changes would be required; there would be no degradation of power; and the ability to change from NG to diesel with the engine running would be provided. These features would allow the railroads to:

1- Opt out of utilizing natural gas in their locomotives and revert to running on diesel oil without incurring reconversion costs, should this for any reason become necessary.

2- Operate satisfactorily on diesel fuel in those geographical areas where supplies of natural gas might be available initially.

3- Use whichever fuel is cheapest as dictated by geographic and market conditions.

Except for the Burlington Northern Railroad, no other concern has seen fit to invest time and money in investigating the viability of a diesel locomotive fueled by natural gas.

4.2 Locomotive Conversion

For this preliminary stage of the program, a Bombardier M420 locomotive was selected, being a typical medium size freight unit and similar to Bombardier's R & D test locomotive.

This similarity offered the possibility to visualize the extent and impact of changes which should not be easily seen from drawings and layouts. Also, should this be necessary, The R & D locomotive could be available for demonstration purposes.

The items listed below are those required to convert a typical Bombardier locomotive to dual-fuel capability.

Components to be Removed and Replaced

A. Exhaust manifold
B. Turbocharger and support
C. Water header branch pipe
D. Fuel injector & nozzles
E. Air elbows
F. Fuel injection pumps (15mm)
G. Governor & governor drive, (actuators) "dual"
H. Exhaust stack

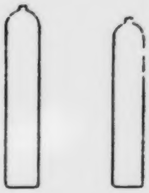
New components to be Added:

A. Gas injection valve assembly
B. Main gas header piping
C. Gas inlet shut-off valve and piping
D. Woodward 501 controller and connecting lines
E. Fire protection and safety equipment
F. Waste-gate valve & piping
G. Change lub oil feed pipe to governor from main header
H. Bracket for waste-gate pipe.

5. FUEL TENDER

The design of the tender is not within the scope of this project. However, it was necessary to define the fuel supply required and method of storage for both the initial demonstration and the final line-haul evaluation should the program continue to its stated objective.

The choice of CNG vs. LNG is dependent on locomotive application and availability. CNG is the cheapest of the two to produce but LNG costs less to store and transport. The ratio of gas to liquid ratio is 625:1 BNR is planning to use two LNG gas tenders with a capacity of 56.779-60,565 litres(12,490-13,332 gal.)which will substantially extend the range of a four-unit consist compared to diesel fueled locomotives.



VEHICLE CYLINDERS
51"-350 Cu.Ft.
56-372 Cu.Ft.

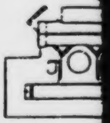


FIG
1-22

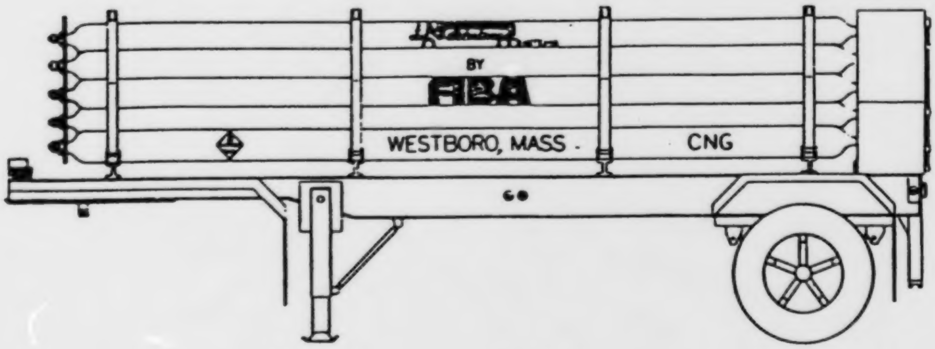
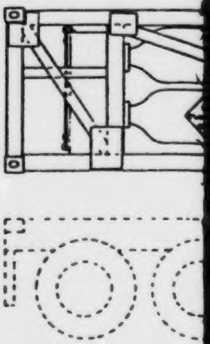

BY
FIBA
WESTBORO, MASS.
CNG

FIG 1 - CONVENTIONAL TUBE TRAILER
30 TUBES @ 1,835 CU.FT. PER TUBE
OR 55,050 CU.FT TOTAL



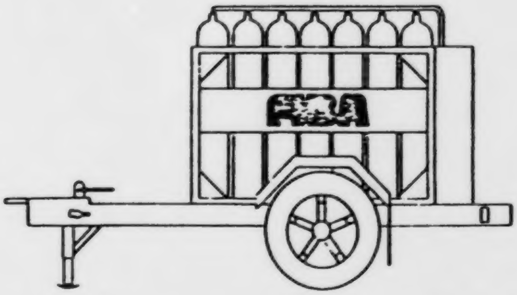


FIG 2 - SHORT DISTANCE DELIVERY UNIT
28 CYLINDERS @ 450 CU.FT PER CYLINDER
OR 12,600 CU.FT TOTAL

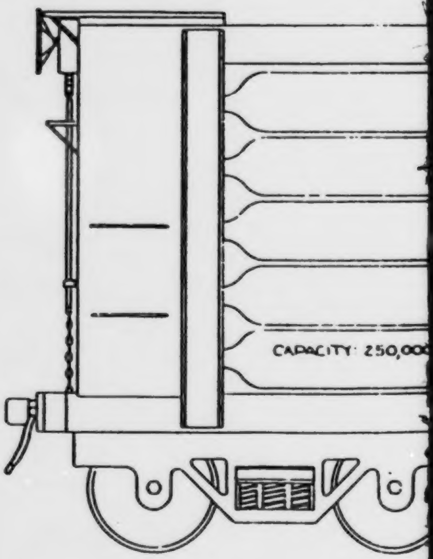

CAPACITY: 250,000

FIGURE 5-1 – C

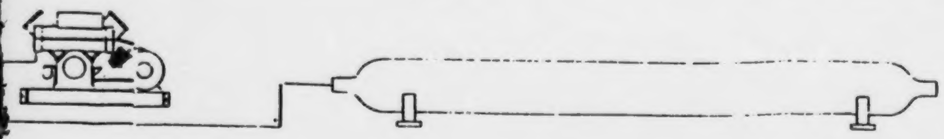


FIG 3- PREPIPED AND WIRED COMPRESSOR AND STORAGE SYSTEMS

1-22" x 20' TUBE - 10,670 CU FT. ASME-approved tubes.

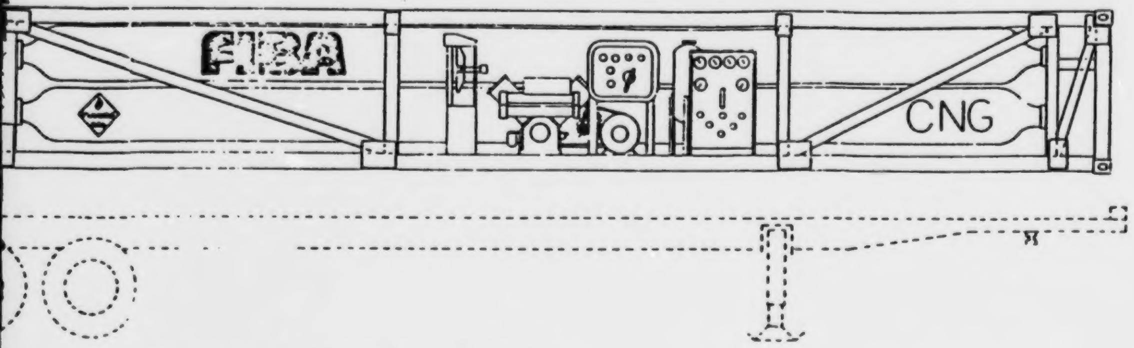


FIG. 4 - FIBA ISO DROP-IN PACKAGE
4 TUBES @ 8,333 CU.FT. PER TUBE
OR 33,332 CU.FT. TOTAL WITH PRE-PIPED AND WIRED COMPRESSOR SYSTEM

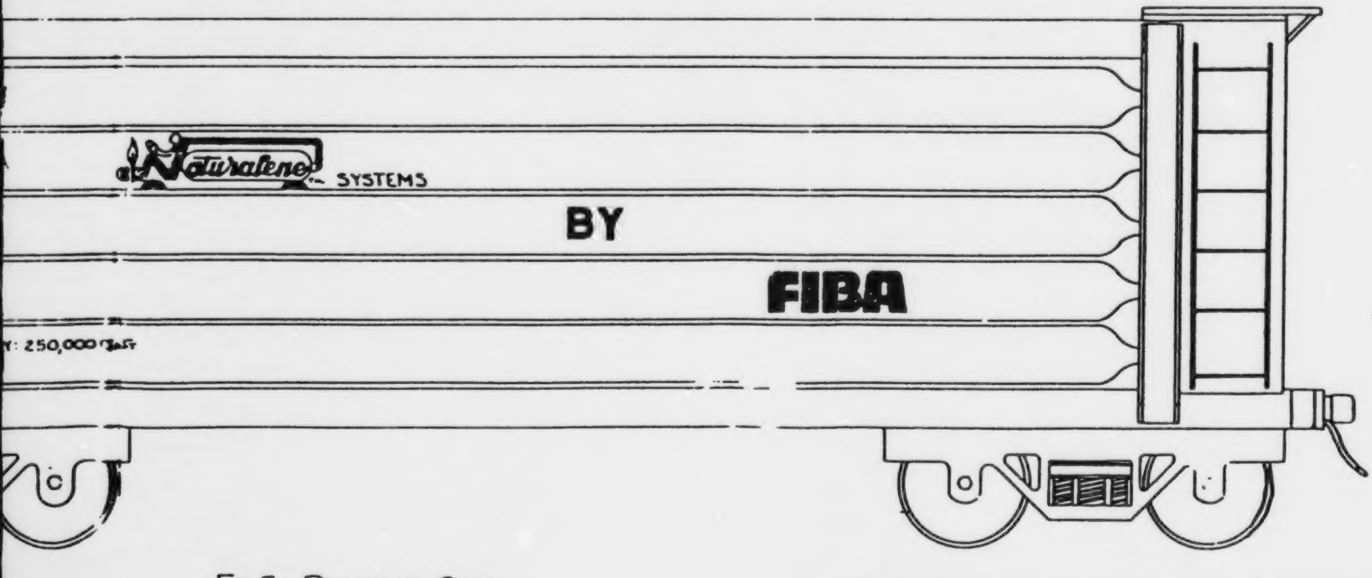

Naturalene SYSTEMS
BY
FIBA
Y: 250,000 CuFt

FIG 5 - RAILROAD CAR
30 TUBES @ 8,333 CU FT PER TUBE OR 250,000 CU FT TOTAL

1 — CNG TENDER

FIBA CRYOGENIC AND COMPRESSED GAS EQUIPMENT
97 TURNPIKE ROAD, WESTBORO, MA. 01581

NATURALENE™ TRANSPORT, STORAGE SYSTEMS

12/17/80

18

The boiling point of LNG is -161.5°C (-258.7°F). Therefore, cryogenic tanks are used to transport LNG. Although highway cryogenic tank trailers have moved LNG in Canada and the U.S., LNG has not been transported on the railroad. In March 1986, the FRA issued a new series of test requirements for railway tank cars and highway tank trailer (in piggyback service).

As stated earlier, BNR is the only concern to have an actual program in progress. The BNR consortium includes Air Products Corporation,a manufacturer of gas handling equipment. The design, development, testing and FRA review of a railway cryogenic NG tank car have been underway for some time. It is reasonable to assume that the approval and acceptance of a LNG tender in the U.S. would also be approved by Canadian regulatory bodies.

In applications such as the initial demonstration, it is economical to utilize a locomotive tender design as shown on Fig. 5.1 which is an adaptation of the multi-modal transport concept. It should be noted that the BNR tender configuration is a truck tube trailer fixed to a flat car. These systems include regulator valves which reduce the storage gas pressure, vaporisers and safety shut off valve.

6. DEMONSTRATION

Accepted railway practice currently dictates that cars containing hazardous commodities be positioned at least six cars from the front of the train (locomotive). This practice presents obvious logistic problems. The choice of a private dedicated railroad removes this problem.

Kidd Creek Mines of Timmins, Ontario, has given its moral support to this project from the initial discussion stage. This facility satisfies the basic criterion of the test site due to its dedicated railway system and proximity to the pipeline. Also, maintenance facilities were available. After a visit to Kidd Creek by the potential participants in the demonstration (MEny, BRDPD, FIBA CANNING and ICG), a preliminary demonstration plan was discussed and formulated (see Fig. 6 - Logic diagram). It became apparent that Kidd Creek would not be able to remove one of its locomotives from service for the conversion period. Therefore, it is tentatively planned to convert Bombardier's R&D locomotive.

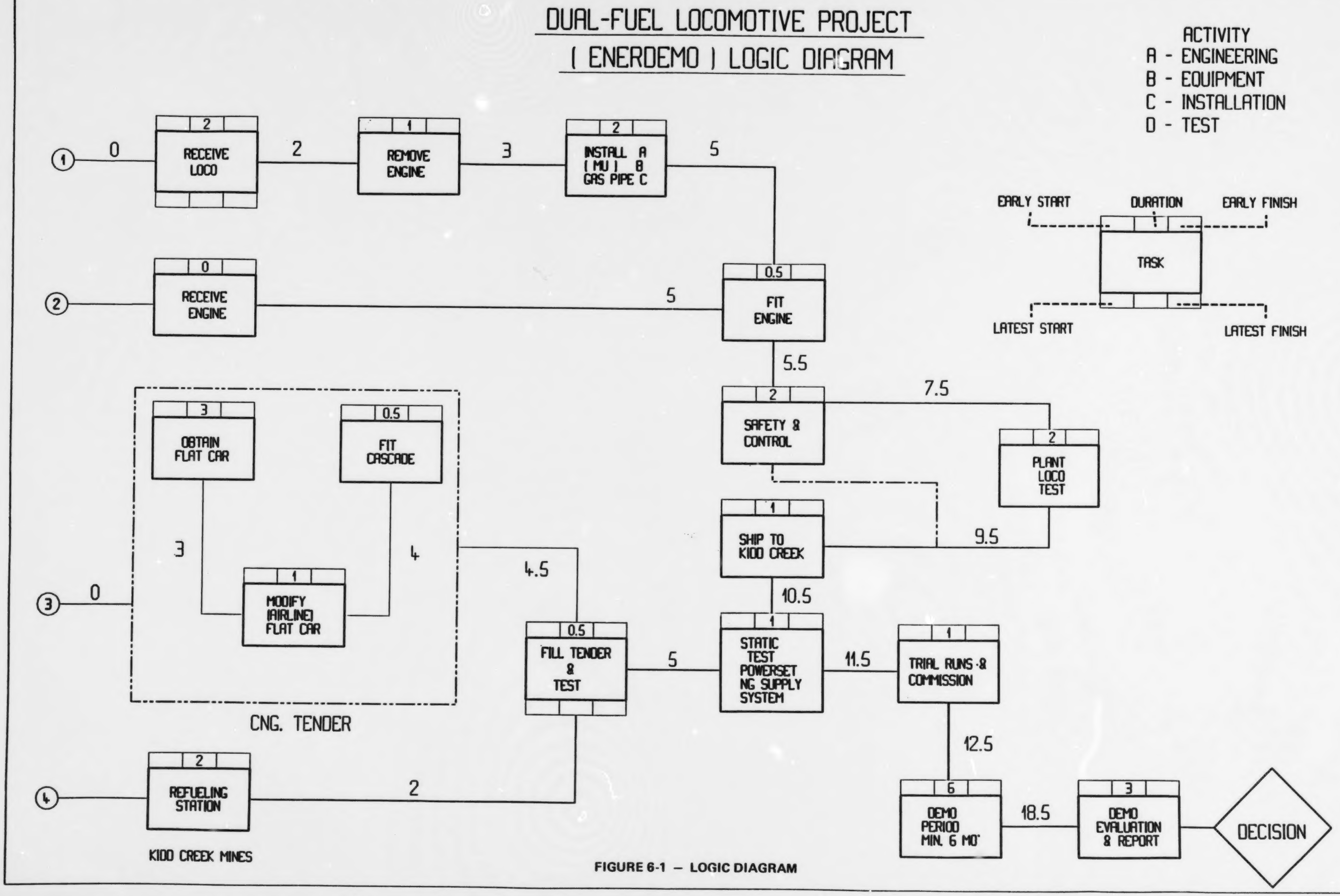

DUAL-FUEL LOCOMOTIVE PROJECT
(ENERDEMO) LOGIC DIAGRAM
ACTIVITY
A - ENGINEERING
B - EQUIPMENT
C - INSTALLATION
D - TEST
EARLY START
DURATION
EARLY FINISH
TASK
LATEST START
LATEST FINISH
①
0
2
RECEIVE LOCO
2
1
REMOVE ENGINE
3
2
INSTALL A (MU) B GAS PIPE C
5
②
0
RECEIVE ENGINE
5
0.5
FIT ENGINE
5.5
2
SAFETY & CONTROL
7.5
2
PLANT LOCO TEST
9.5
1
SHIP TO KIDD CREEK
10.5
③
0
3
OBTAIN FLAT CAR
0.5
FIT CASCADE
3
4
1
MODIFY (AIRLINE) FLAT CAR
CNG. TENDER
4.5
0.5
FILL TENDER & TEST
5
1
STATIC TEST POWERSET NG SUPPLY SYSTEM
11.5
1
TRIAL RUNS & COMMISSION
12.5
④
2
REFUELING STATION
KIDD CREEK MINES
2
6
DEMO PERIOD MIN. 6 MO'
18.5
3
DEMO EVALUATION & REPORT
DECISION

FIGURE 6-1 — LOGIC DIAGRAM

7. PHASE 3 - ENGINE DEVELOPMENT: ADVANCED TECHNOLOGY

The dual-fuel(DF) engine can achieve higher combustion efficiency over the spark ignition(SI) cycle due to the thousands if ignition sources and can operate in leaner air-fuel mixtures . Its advantages over the diesel cycle is that it can use gaseous fuels which are cheaper than diesel fuel.

Most DF engines are built as diesel engines because the hardware is similar and usually designed to run as both DF and diesel engines with the capability to switch modes under load. The flexibility of this dual-purpose configuration demanded certain compromises in the past which can be eliminated by today's technology

In reviewing the 1950's design, the following appear to inhibit the achievement of optimum performance:

1. Pilot fuel was provided by using the standard diesel fuel system at low rack settings. This had the following limitations:

    a. Pilot fuel timing had to be the same as full diesel fuel timing.

    b. Pilot fuel injection nozzle (and spray pattern) had to be the same as fuel diesel.

    c. Special precautions had to be taken to ensure stable injection of pilot fuel.

2. The gas admission valve was driven by the intake valve linkage; timing and duration of gas admission were therefore locked into intake valve timing. The large amounts of scavenge air required for today's higher rating would create considerable carry-over of gas into the exhaust manifold, which, is, of course, highly undesirable.

3. Turbocharger matching was compromised, and no consideration was given to waste-gating or by-passing, since reliable hardware was not available.

4. The control system was entirely mechanical, costly to manufacture and difficult to adjust. Governing in the dual-fuel mode was effected by the governor adjusting the gas supply manifold pressure.'

7.1 Technical Approach

The technical approach will be to study the engine performance as affected by changes in intake and exhaust valve timing and duration; pilot injection timing, duration and quantity; and turbocharger characteristics.

A matrix of tests will be conducted to study which the thermal efficiency effects due to the following:

- Compression ratio
- Knock limit
- Lean limit (pilot fuel)
- Intake air throttling
- Fuel-air ratio
- Lean flammability limit (gas/air)
- Gas admission techniques.

Microprocessor-based programmable control systems, electronic fuel injectors and solenoid-activated gas admission valves will be employed. These systems are all available. However, this advanced technology has not been applied to the medium-speed diesel engine.

7.2 Scope of work

In order to reduce cost and time, a BSCRE-DF will be the test engine. A multi-cylinder engine will only be used where inter-cylinder affects, and optimum performance is required.

Part A - Single Cylinder

1. Computer analysis of combustion: Predict critical factors affecting performance, with particular emphasis on gas mode;
2. Pilot ignition investigation:
    a) Optimization and/or modification of normal diesel fuel injection equipment (the traditional approach);
    b) Separate pilot injection system.

Part B - Multi-cylinder

1. Waste-gate and by-pass valves: Obtain prototype and determine their performance characteristics.
2. Controls: Based on test data acquired, prepare a control strategy and preliminary design test prototype on single-cylinder.
3. Multi-cylinder engine testing: Conduct tests on multi-cylinder engine, having made preliminary evaluation on single-cylinder; optimize and refine manifolding, waste-gate, controls, etc. Establish complete performance map and obtain appropriate transient performance.

8. CONCLUSION

The objectives of the project, which are to perform the necessary task to establish the strategy for demonstrating the operation of a dual-fuel rail locomotive, have been defined in detail.

The literature review gave an understanding of the progress made in dual-fuel NG burning engines. The review also revealed that very little work has been directed to the large bore medium-speed engine. Only the BN dual-fuel locomotive program and its promising results were found to impact this program. From this literature review limitations, technical approach and the potential accomplishments derived.

Improvements which were made on the Bombardier 251 SI engine were transferred to the 251-DF engine. Application of the electronic governor, waste-gate and dual electric actuators will produce better performance than the 251-DF of 30 years past.

The new interactions and unknowns associated with locomotive application, particularly with regards to operational logistics and safety can, in most respects, be visualized and therefore answered only in an on-rail demonstration. Hence the possible inclusion of a dual-fuel locomotive as part of the "ENERDEMO" Program of Energy, Mines and Resources Canada.

It is recommended that all effort and support be applied to ensure the continuance of this program past. Phase II (current technology conversion). Long-term R & D as outlined in Phase III will ultimately remove or extend the limits which prevent equal thermal efficiency of the dual-fuel gas engine and diesel engine.

The dual-fuel engine has major advantages such as flexibility, low emissions and minimum use of diesel fuel.

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APPENDIX "A"

LITERATURE SEARCH: - REVIEWED ABSTRACT

A LITERATURE SEARCH FOR THIS REPORT PRODUCED THE FOLLOWING PAPERS

NATURAL GAS THE NEW LOCOMOTIVE FUEL

by Lee W. Tuskey, Supervising Research Engineer, Northern States Power Company

The purpose of this paper is to report on the conversion of a locomotive diesel engine to a dual-fuel engine. A compressed natural gas (CNG) fuel tender will supply gas fuel to the locomotive. The locomotive has been modified and the static (load box) tests commenced in September 1983. After completion of the static tests the locomotive will be tested in line haul railway service. If the tests in actual train service are successful a significant step will have been accomplished in the development of a locomotive that is capable of using an alternative to diesel fuel and yet provide high engine performance but reduce fuel and maintenance costs.

INTRODUCTION OF A COMMERCIAL SYSTEM FOR LIQUID METHANE VEHICLES

by Felix L. Fischer, Program Manager - Alternate Fuels, Beech Aircraft Corporation, Boulder, Colorado

Commercialisation of numerous alternate fuel systems for vehicles is now taking place. Beech Aircraft Corporation has developed a system using liquid methane (LM) as a vehicle fuel and is now marketing vehicle conversion systems, fueling equipment, and total systems integration capability.

The Beech LM system is designed to provide the user with operating characteristics similar to gasoline systems. Dispensing equipment, fueling stations, and vehicle systems maintain a high level of familiarity to the user/operator which enhances training and general acceptance. Safety, as well as quality and ease of operation, have been designed into all aspects of the overall system.

GASEOUS FUEL SAFETY ASSESSMENT FOR LIGHT-DUTY AUTOMOTIVE VEHICLES

by M.C. Krupka, A.T. Peaslee, H.L. Laquer - Los Alamos, New Mexico

We assessed the relative safety of gaseous and liquid fuels utilised for light-duty automotive transportation. The specific fuels considered were compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), and as reference, gasoline and diesel fuel.

The assessment methodology describes and develops the relative hazards of these fuels from an integrated generic physicochemical property and accident scenario point of view. We established fuel-relative safety rankings by eliciting expert judgment and combining that judgment with a comparative scoring methodology.

Selected accident scenarios included fuel leakage in both residential and public garages; fueling line rupture at a refueling station in the presence of user vehicles or delivery vehicles; and vehicle collisions under rural, urban, and vehicular tunnel conditions. Our results permit the generation of selected safe handling criteria.

LNG DRIVE SYSTEMS FOR BUSES

by Lotepro Engineering and Construction Ltd., Calgary, Alberta

LNG DRIVE SYSTEMS FOR ROAD VEHICLES

by Ing.(grad.) Karl Ruppert, Pullach

In Linde AG, the starting point for developing an LNG fuel plant and an LNG filling station was the activity of the automotive industry in the field of natural-gas-driven utility vehicles, and particularly the development of a natural-gas-driven bus.

In 1972, in co-operation with the firm of Daimler-Benz, Linde AG fitted an experimental bus with an LNG-fuel plant. This bus has been in operation ever since. The fuel system continues to operate without trouble.

As a result of the experience gained so far it can be stated that the technical problems involved in the operation of road vehicles by means of LNG have been satisfactorily solved. From the low-temperature-engineering point of view there is nothing to prevent the increased use of LNG as a fuel.

CANADIAN RAILWAY ENERGY CONSERVATION AND ALTERNATIVE FUELS

by G.W. English, R.W. Lake, M.D. Roney, J. Taggart - Canadian Institute of Guided Ground Transport, Queen's University at Kingston, Ontario

Possibilities for energy conservation and energy substitution within the rail mode are investigated. Estimates are made of potential energy infrastructure changes. The status of alternative hydrocarbon fuels in railway applications is assessed and alternative energy systems are evaluated. Recommendations are made for railway implementation of some points and further investigation of others.

ENERGY IN TRANSPORT - DATA

by Beca Carter Hollings & Ferner Ltd., for New Zealand Energy Research and Development Committee, University of Auckland, New Zealand.

Detailed information is presented on energy use in New Zealand transport together with international comparisons and historical trends. The term transport energy as used here refers to direct energy use, that is the energy supplied for vehicle propulsion, being the energy content of the fuel or electricity consumed. The data tabulations are for the whole transport system, broken down into various subdivisions. Such "system-wide" data, unless they are disaggregated to a very fine level, do not generally show up the attributes of particular transport vehicles, and for this reason have been criticised overseas. To avoid this error of omission data are also presented on particular transport vehicles apart from the main data sets. Wherever possible, to eliminate cumulative errors, global data have been used as control totals and a process adopted of successive breakdown into subdivisions of the transport system. Only in a few cases, where New Zealand data are lacking and could not be inferred, have overseas data been introduced and then only when these were judged to be reasonably applicable to the New Zealand situation.

THE AAR HANDBOOK OF ALTERNATIVE LOCOMOTIVE FUELS

by Research & Test Department, Association of American Railroads

A reference document describing physical properties and medium-speed diesel engine performance with a variety of liquid fuels that may be available. Fuel handling suggestions are included for both terminal storage and on-board the locomotive. Each fuel is rated on its engineering acceptability in locomotive diesel engines. No rating is given for economic feasibility.

SOME SAFETY MEASURES IN AN ENGINE INVESTIGATION

by G.A. Karim, Ph.D., D.I.C., B.Sc.(Eng.), G.I.Mech.E., Mechanical Engineering Department, Imperial College, London

A review is made of some of the safety measures adopted in the investigation of the combustion of methane-air-oxygen system in an unmodified single-cylinder engine operating on the dual fuel principle which was carried out by the author in association with Mr. N.P.W. Moore at Imperial College.

THE KNOCK AND AUTOIGNITION CHARACTERISTICS OF SOME GASEOUS FUELS AND THEIR MIXTURES

by G.A. Karim, Ph.D., D.I.C., B.Sc., A.M.I.Mech.E., and S.R. Klat, Ph.D., B.Sc., A.C.G.I., Mechanical Engineering Department, City and Guilds College, Imperial College, London

The knock and autoignition characteristics of some common gaseous fuels, namely methane, propane, ethylene and hydrogen together with some of their mixtures, were observed and recorded systematically over a wide range of mixture strength and intake temperature when employing a CFR-"Motor Method" engine. It is shown that such data, in addition to providing general information regarding the limits of performance of high-compression-ratio gas engines, can form a basis for correlating the limits of dual-fuel engine operation.

KNOCK IN DUAL-FUEL ENGINES

by G.A. Karim, Ph.D., C.Eng., A.M.I.Mech.E., S.R. Klat, Ph.D., and N.P.W. Moore, B.Sc., C.Eng., M.I.Mech.E., Mechanical Engineering Department, Imperial College, London

The paper describes some aspects of the findings of an investigation which was initiated mainly to obtain a better understanding of the phenomenon of knock under dual-fuel operation and to determine the effect of various operating parameters on the knock-free performance limits and the nature of these limits. Some common gaseous fuels such as methane, propane, ethylene, acetylene, hydrogen and some of their mixtures were used as the main fuels. A method is suggested to relate changes in the knock-limited power output of a dual-fuel engine with the intake temperature of the charge and the nature of the main fuel used.

THE IGNITION OF A PREMIXED FUEL AND AIR CHARGE BY PILOT FUEL SPRAY INJECTION WITH REFERENCE TO DUAL-FUEL COMBUSTION

by G.A. Karim, Mechanical Engineering Department, Imperial College of Science and Technology

Dual fuel engines compress the air/gas fuel mixture to just below autoignition conditions and then ignite it by the injection of a small amount of liquid fuel. The use and performance of these engines, however, have been limited by knock. Single cylinder engine experiments show that this limitation is a readily defined auto-ignition phenomenon, and can be analyzed by a mathematical model that indicates the effects on performance imposed by fuel changes and operating

conditions. Experimental findings confirm that these performance data correlate broadly with those obtained conventionally in standard spark ignited or motored engines.

SOME ASPECTS OF THE UTILIZATION OF LNG FOR THE PRODUCTION OF POWER IN I.C. ENGINES

by G.A. Karim, Mechanical Engineering Department, The University of Calgary, Alberta

Review is made of the main technical aspects of the utilization of natural gas as the primary fuel in internal combustion engines of both the piston and gas turbine types for the production of power. This review is then extended to consider the further problems brought forward by the utilization of LNG in conventional internal combustion power plants.

Many of the technical problems arising from the applications of LNG in engines are similar to those when NG is the fuel. Much research and experience in this area exist. There is, however, very much less information regarding the further problems brought about by the relatively high heat sink of LNG when used as an engine fuel. Expansion in this field of application of LNG is very much dependent on the further technological advances needed for the handling of a cryogenic fluid in everyday applications.

THE COMBUSTION OF METHANE WITH REFERENCE TO ITS UTILIZATION IN POWER SYSTEMS

by Professor G.A. Karim, Ph.D., D.I.C., C.Eng., M.I.Mech.E., and M.V. D'Souza, M.Sc., D.I.C., Department of Mechanical Engineering, University of Calgary, Alberta

The main combustion problems associated with the employment of natural gas as an engine fuel are reviewed. The high temperature oxidation of methane is considered and an analytical model developed to investigate the combustion of methane in a flow system using a reaction scheme consisting of 24 reaction steps and involving 15 species. Over the range of conditions investigated, calculated values of the induction period agreed well with experimental results reported in the literature. Moreover, the calculated concentrations profiles indicated trends similar to those observed experimentally by other workers.

THE EFFECTS OF LOW AMBIENT TEMPERATURES ON THE COMBUSTION OF NATURAL GAS IN A SINGLE-CYLINDER SPARK IGNITION ENGINE

by G.A. Karim, University of Calgary, Alberta, and I.A. Ali, Ahmadu Bello University, Nigeria

Operating characteristics including ignition limits, cyclic variability, and exhaust emissions were studied in the combustion of natural gas in a spark ignition, single-cylinder, variable compression ratio engine, operated at intake mixture temperatures ranging between 120 and -60 F.

The work confirmed in general the feasibility of using natural gas in a spark ignition engine operated under extremely cold intake temperature conditions. It was learned that both the maximum peak cylinder pressures and the mass of mixture inducted by the engine increased as the intake mixture temperature was lowered, and that the emissions of pollutants were not significantly increased.

These findings are thought to be particularly relevant to the use of natural gas in spark ignition engines, either as LNG or under very cold wintry conditions.

EXPERIMENTAL AND ANALYTICAL STUDIES OF HYDROGEN AS A FUEL IN COMPRESSION IGNITION ENGINES

by G.A. Karim and S.R. Klat, Department of Mechanical Engineering, University of Calgary, Alberta

This paper presents some of the findings of an investigation into the performance of a compression ignition engine when fuelled with hydrogen. Most of the experimental work reported was carried out in a laboratory dual fuel engine where hydrogen was introduced just outside the engine cylinder, mixed with the necessary air, compressed and then ignited by the injection of a small quantity of liquid fuel near the end of compression. Moreover, the role of various operating parameters on the onset of autoignition in a motored engine in the absence of a deliberate source of ignition was also established analytically. Comparison with experimental observations is also included.

COMBUSTION, KNOCK AND EMISSION CHARACTERISTICS OF A NATURAL GAS FUELLED SPARK IGNITION ENGINE WITH PARTICULAR REFERENCE TO LOW INTAKE TEMPERATURE CONDITIONS

by G.A. Karim, Department of Mechanical Engineering, University of Calgary, Alberta, and I.A. Ali, School of Technology, Kwara State College, Ilosia, Nigeria

For various fuel-air mixtures and different compression ratios, the intake temperature was varied over the entire range of 200 F (366K) down to -100 F (200K) when employing a single cylinder spark ignited research engine fuelled with natural gas. Performance data such as knock and ignition limits, the nature and extent of exhaust emission and chamber pressure cyclic variation were obtained. Means were then suggested for the interpretation of the above mentioned data in terms of engine operation on liquefied natural gas. The experimental work confirmed in general the attractive features of the use of natural gas as a fuel in a spark ignition engine operated under extremely cold intake temperature conditions and that emissions of pollutants were not significantly increased.

THE COMBUSTION OF GASEOUS FUELS IN A DUAL FUEL ENGINE OF THE COMPRESSION IGNITION TYPE WITH PARTICULAR REFERENCE TO COLD INTAKE TEMPERATURE CONDITIONS

by G.A. Karim and K.S. Burn, Department of Mechanical Engineering, University of Calgary, Alberta

The present contribution is mainly concerned with an investigation of the characteristics of dual fuel operation under cold intake temperatures, primarily from the viewpoint of engine performance and exhaust emissions. The gaseous fuels employed were methane, propane, hydrogen and ethylene. The addition of the inerts carbon dioxide and nitrogen were also considered. Comparison with the corresponding normal diesel operation was made throughout.

EXAMINATION OF THE PERFORMANCE OF A DUAL FUEL DIESEL ENGINE WITH PARTICULAR REFERENCE TO THE PRESENCE OF SOME INERT DILUENTS IN THE ENGINE INTAKE CHARGE

by G.A. Karim and N. Amoozegar, Department of Mechanical Engineering, University of Calgary, Alberta

An examination of the combustion phenomena and associated engine performance is made for a dual fuel engine of the compression ignition type when additional auxiliary fuels and inerts were introduced with the main intake charge. This was considered to have direct relevance to operation of diesel engines on low heating value gaseous fuel mixtures. A single cylinder direct injection diesel engine was employed throughout. H_2, CH_4, CO_2 and N_2 were the gas constituents used.

Operation on gaseous fuel mixtures containing significant amounts of diluent inerts showed a market deterioration of the already inefficient combustion of lean fuel-air mixtures. Of the two inert gases (CO_2 and N_2) introduced in turn, CO_2 has a comparatively greater influence in narrowing the operating range of the engine.

Both diesel and dual fuel operations were also considered when a spray of water was introduced into the intake of the engine. The quenching of the charge resulting from water addition appeared to slow down the combustion rates, necessitating the supply of a certain minimum amount of gaseous fuel and diesel pilot for adequate combustion.

SOME CONSIDERATIONS OF THE SAFETY OF METHANE, (CNG), AS AN AUTOMOTIVE FUEL - COMPARISON WITH GASOLINE, PROPANE AND HYDROGEN OPERATION

by G.A. Karim, Department of Mechanical Engineering, University of Calgary, Alberta

The total number of vehicles fuelled with compressed natural gas, CNG, is relatively very small in comparison to gasoline fuelled vehicles. Accordingly, because of the lack of statistics of accidents involving CNG fuelled vehicles, their safety aspects are evaluated in comparison to automobiles fuelled with gasoline or some other alternative fuels such as propane, hydrogen, LNG or LH_2. It is suggested that methane, CNG, has some excellent physical, chemical and combustion characteristics that make it a safe automotive fuel. These characteristics are reviewed and the superior relative safety of methane in automotive applications in comparison to applications involving the other fuels is demonstrated where well designed conversion systems and operations are employed.

THE DUAL FUEL ENGINE OF THE COMPRESSION IGNITION TYPE - PROSPECTS, PROBLEMS AND SOLUTIONS - A REVIEW

by G.A. Karim, Department of Mechanical Engineering, University of Calgary, Alberta

A review is made of some of the main problems associated with the use of natural gas, notably methane, in dual fuel engines of the compression ignition diesel type. It is shown that such applications represent in principle a very attractive mode for the utilization of the fuel for the production of power generally at relatively high efficiencies and outputs with good exhaust emissions characteristics. Some relevant solutions to the problems outlined are then discussed. Moreover, some further research and development needed in this general area is also outlined.

PLANNING OF GAS ENGINE PLANTS

by M.A.N. (Maschinenfabrik Augsburg-Nurnberg)

Pipelines for natural gas are being extended more and more and sewage gas production is continually on the increase. The conversion of gaseous fuel into electrical or mechanical energy by means of gas engines and the recovery of engine exhaust heat suggest themselves for processing and space heating. It is especially in the past few years that the development trend has been towards gas engine plants of higher outputs. Gas engines are suited as prime movers for a great variety of machines such as generators, pumps, compressors, etc. for use in industrial plants, sewage stations and pipeline operation. For years, M.A.N. have been actively engaged in developing suitable propulsion engines. Today the Augsburg Works of M.A.N. are in a position to supply gas engines with ratings of up to 13,500 horse-power. Development is based on the experience gained from Diesel engines, i.e. well-proven components are being adopted from the Diesel engine.

This brochure deals with the planning and construction of complete energy generating plants burning gaseous fuels.

M.A.N. DUAL-FUEL ENGINES WITH HIGH MECHANICAL AND THERMAL EFFICIENCIES - A MORE ECOLOGY-ORIENTED INTERNAL COMBUSTION ENGINE ALTERNATIVE

by Wolfgang Klaunig, M.A.N. B&W

Like the Diesel engine, the dual-fuel engine has a long tradition as being one of the most economical types of heat engine. Depending on the particular demands of the customer, these engines can be optimised with regard to output and utilisation of the most varied types of gas; in addition, these engines are used in various drive applications, especially in generators and compressors.

In recent times there has been an increased demand for the recovery of waste heat from cooling water, engine oil and exhaust gas and it is this demand in particular which has promoted the application of dual-fuel engines, e.g. in co-generation plants.

CONVERTING A SMALL CAR TO LNG: WHAT ARE THE PROBLEMS AND WHAT CAN IT DO FOR ECONOMY AND EMISSIONS?

by W.A. Affleck, G.A. Harrow, and W.D. Mills, Shell Research Ltd.
(United Kingdom)

A two litre compact car originally designed to run on gasoline has been converted to run on LNG. Comparative measurements of fuel economy and exhaust emissions were made for the same car running on each fuel under normal on-the-road and simulated taxi service. When tuned to its maximum economy configuration the LNG car gave significant improvements in fuel economy when expressed on an energy basis. For inter-urban journeys the savings would be of the order of 5% and for taxi type service in excess of 20%. Whether or not these savings would justify fleet conversion would depend on local fuel cost and taxation conditions.

When set for maximum economy the LNG car gave significantly lower emissions of CO and hydrocarbons than its gasoline counterpart. Emissions of NO_x were, however, higher with LNG than with gasoline. A tenfold reduction in NO_x emissions could be obtained by re-tuning the LNG engine to run at air/fuel ratios up to 30:1. Hydrocarbon emissions with this configuration were, however, quite high and would require supplementary means of control. When tuned to operate at very weak mixtures the car remained quite driveable but was 10 to 15% less economical than when tuned for maximum economy.

Although technically practical, the use of LNG is likely to be restricted by supply and distribution limitations to fleet operators and other high mileage users who could refuel from centralized points where trained staff would be available.

DUAL-FUEL ENGINES AS PROPULSION PLANTS FOR LIQUEFIED GAS TANKERS

by W. Klaunig, K. Will and H. Kern, M.A.N., Augsburg

The article shows that the dual-fuel engine is now sufficiently developed to be ready for installation as the propulsion unit in a gas tanker.

Safety measures in the dual-fuel engine are comprehensive, the design has been based on the well-tried diesel engine and dual-fuel units have been proved in stationary plants for a number of years. Plans for propulsion plants of liquefied natural gas tankers have been prepared at M.A.N. using various dual-fuel engine groupings.

ALTERNATIVE FUELS FOR LOCOMOTIVE DIESEL ENGINES

by E.M. Goodger, B.Sc., M.Sc., Ph.D., C.Eng., M.I.Mech.E., I.I.E.Aust., M.R.Ae.S., F.Inst.E., F.Inst.Pet., Cranfield Institute of Technology, Bedford

Synthesis of elemental hydrogen and carbon to hydrocarbon fuels suited to locomotive diesel engines is technically feasible but energetically unattractive. More promising are long-term substitute fuels which may be derived from plentiful, or preferably replenishable, sources, and which could act also as extenders to conventional fuels in the short term. The availabilities and properties of a range of substitute fuels are examined, together with their published performance data in relation to the method of introduction to the engine combustion chamber. Overall, the alcohols, vegetable oils and, to some extent, slurry fuels are rated as viable, whereas the liquefied gases and nitrogen compounds are rejected.

NO_x EMISSION REDUCTION METHODS FOR LARGE BORE DIESEL AND NATURAL GAS ENGINES

by Fred S. Schaub and Kenneth V. Beightol, Engineering Research Laboratory, Cooper-Bessemer Co., Mount Vernon, Ohio

Test results showing exhaust-gas emission levels for three types of large bore nonvehicular engines are reported in this paper. Also reported are the effects of nonstandard engine operating conditions on emission levels. These results are being offered to the industry as introductory information. The authors also discuss solutions to several problems encountered in developing satisfactory analytical techniques.

COMPUTER BASED COGENERATION PACKAGE

from Diesel Progress North America

The author describes a new line of packaged cogeneration modules. The units are available in diesel or natural gas configurations, and include the equipment required for a complete cogeneration system in a single housing. They include a special module incorporating a newly developed microprocessor-based control system. The main advantage of a packaged cogeneration module is the single source responsibility. A packaged system also greatly reduces the amount of on-site installation work required.

SOME CONSIDERATIONS OF THE USE OF NATURAL GAS IN DIESEL ENGINES

by Ghazi A. Karim, Ph.D., D.Sc., Professor, Department of Mechanical Engineering, University of Calgary, Alberta

Review is being made of the problems associated with the use of natural gas, notably methane in dual-fuel engines of the compression ignition diesel type. It is shown that such applications represent a very attractive mode for the utilization of the fuel for the production of power generally at relatively high efficiencies and outputs with superior emissions characteristics. Some of the problems associated with such applications are discussed and some relevant solutions outlined.

COMPARATIVE STUDIES OF METHANE AND PROPANE AS FUELS FOR SPARK IGNITION AND COMPRESSION IGNITION ENGINES

by G.A. Karim and I. Wierzba, Department of Mechanical Engineering, University of Calgary, Alberta

The paper reviews the combustion characteristics of the two fuels and sets out to consider their respective performance in both spark ignition and compression ignition engines. Results of comparative tests involving spark ignition engines over a wide range of operating conditions are presented and discussed. Some of the performance characteristics considered are those relating to power output, efficiency, tendency to knock, cyclic variations, optimum spark requirements and exhaust emissions.

Similarly, some of the performance characteristics in compression ignition engines considered include power output, efficiency, tendency towards knock and auto-ignition, exhaust emissions and low operational temperature problems.

Finally, the relative operational safety aspects of the two fuels are evaluated. It is then suggested that in this regard, methane has some excellent physical, chemical and combustion characteristics that makes it a particularly safe fuel.

METHANE AND DIESEL ENGINES

by G.A. Karim, Department of Mechanical Engineering, University of Calgary Alberta

This paper makes a comparison between a spark ignited gas engine operating on methane alone relative to a similar diesel engine also operating on methane. For an engine operating as a spark ignition gas engine, the two-stroke mode is of relatively poor efficiency; while turbo-charging the two-stroke, particularly when it is well done, can improve the specific fuel consumption significantly. The four-stroke turbocharged engine operating on gas and spark ignited, has an efficiency that is superior to that of the two-stroke. On the other hand, diesel-gas operation is generally superior to that of spark ignition over the whole load range. Turbocharging the gas-diesel will produce a relatively lower efficiency at light load than the corresponding diesel. However, over the bulk of the higher output range, the turbocharged gas-diesel is far superior to the straight turbocharged diesel both in terms of efficiency and power output. Therefore, the turbocharged gas-diesel is much superior to the spark ignition engine or even the corresponding straight diesel.

BIOMASS - THE ALTERNATIVE FUEL

by Dr.-Ing. H. Zapf and Dr.-Ing. H. Pucher, M.A.N. Augsburg, Abt. Motorenforschung

Reviews the range of fuels manufactured from animal and vegetable biomass, and household and commercial waste and garbage, which can be burned in compression ignition and spark ignition engines.

M.A.N. - GAS ENGINES

by M.A.N.

Reviews the range of M.A.N. gas engines (compression ignition and spark ignition), criteria for choice of engine, dual-fuel engines, gas supply, ignition equipment, changeover devices, safety features, turbo charging, waste heat recovery.

DUAL FUEL SHIP RUNS ON NATURAL GAS - TRAINS ARE NEXT

by Rodney D. Nyman, General Manager, Dual Fuel Systems Pty. Ltd.

Discusses the first ship in the world to run on natural gas - in Australia - and indicates that similar technology could be utilised for locomotives owned by the New South Wales State Railways

SULZER DUAL-FUEL ENGINE FOR LNG SHIPS

from Shipbuilding and Shipping Record

Discusses the incentives for the development of dual-fuel engines for LNG ships, the development procedures which were followed, and the results obtained; details of the design of dual-fuel engines and the structural differences between diesel and dual-fuel engines; fields of application for such engines; savings which could be achieved by replacing steam plant with dual-fuel engines in ships.

THE NORTHERN RAILWAY OPTION

by R.W. Lake and M.D. Roney, Canadian Institute of Guided Ground Transport, Queen's University, Kingston

The author points out that the principal economic advantage of a railway over other modes of transportation of oil and liquefied natural gas from the Arctic lies in its flexibility. A number of railways currently operate in regions of permafrost and one has been doing so for more than forty years. Railway rationale, construction, technology, implementation, economics, etc., are discussed in this article.

DETROIT DIESEL ELECTRONIC CONTROL

by R.J. Hames, R.D. Straub, R.W. Amann, Detroit Diesel Allison Division, General Motors Corporation

This paper presents the design and development of the Detroit Diesel Electronic Control system (DDEC) for heavy duty diesel engines. DDEC is a microprocessor controlled electronic unit injection-engine governing system. The application of microprocessor technology to the unit injection system provides both precision and flexibility in fuel injection timing and metering events through the use of solenoid operated unit injectors. The on-board diagnostic capabilities of the microprocessor provide for system self-diagnostics and, combined with engine oil and water system sensors, offer engine protection diagnostics.

The design and development of the solenoid operated unit injector, the selection of the sensors, and the engine control philosophy are discussed. Injector solenoid performance characteristics and engine data on cold starting, cold smoke, and transient smoke are presented in illustration of design decisions.

CONVERSION OF A DETROIT DIESEL ALLISON TWO STROKE CYCLE ENGINE TO NATURAL GAS/DIESEL OPERATION

by B.C. Stonehill (DSMA ATCON LTD)

This program involves the development of a conversion system to allow the operation of a DDA 6V71 diesel engine on natural gas, with pilot diesel injection to initiate combustion. The 6V71 was chosen since it is the engine used for most Canadian urban buses, but the same system would be readily applied to the 6V92 or other engines of this DDA family.

The program is funded through the Canadian Federal Department of Supply and Services, on behalf of the Ministry of Energy, Mines and Resources, and the work is being carried out by DSMA ATCOM LTD. of Toronto. An engine employing the system is running in the DSMA laboratory.

CONVERTING DIESEL ENGINES TO THE USE OF GASEOUS FUELS

by P. Tiedema, J. van der Weide, H.J. Dekker, Research Institute for Road Vehicles TNO, Delft, the Netherlands

The increasing interest for gaseous fuels in internal combustion engines leads to increased effort to enable diesel engines to run completely or partially on gas. The paper describes three possible approaches, indicates the most attractive one when using producer gas and gives some preliminary results on an engine test using wood gas from a gasifier.

APPENDIX "B"

LEAN-OPERATING LIMIT FOR A DUAL-FUEL NATURAL GAS LOCOMOTIVE

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LEAN OPERATING LIMIT FOR A DUAL-FUEL NATURAL GAS LOCOMOTIVE

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1. INTRODUCTION

Background

This report describes an engineering study which investigated the lower or lean limit of natural gas operation for a Bombardier dual-fuel locomotive. This work is in support of the first phase study of a multi-phase study that Bombardier is conducting for Transport Canada. An important aspect of the first phase is to define practical methods by which existing dual-fuel hardware can be used in a locomotive to maximize natural gas utilization. Phase II will convert a research locomotive to compressed natural gas (CNG) operation using production Bombardier dual-fuel hardware and a CNG tender. Phase III of the program will deal with a more advanced conversion which is not constrained to the hardware limitations mentioned for Phase II.

Economic viability of a natural gas locomotive will largely depend on the amount of natural gas that can be consumed in place of diesel fuel. Natural gas utilization must be high if locomotive and wayside fuel system conversion costs are to be recovered. As a result, the locomotive must be capable of operating over the broadest possible range of operating conditions on natural gas (consistent with good efficiency) and with a minimum of pilot diesel fuel. Stationary engines have demonstrated the ability of dual-fuel natural gas diesels to operate efficiently and with very little pilot diesel fuel in the upper half of their power range. Knocking dictates the maximum power output of a dual-fuel engine, but literature contains numerous citations which show that a dual-fuel engine can equal or exceed the power output of the same engine operated entirely on diesel fuel. Thus, operation in locomotive notches 5 through 8 is expected to produce good performance.

The lowest notch position that can be run in a dual-fuel mode will be dictated by the engine's ability to burn lean fuel air mixtures. Unlike stationary engines, a locomotive dual-fuel engine must be able to operate at low power settings on natural gas. Increasing the pilot diesel fuel amount, a common solution to operational problems near the lean limit, was not considered acceptable for this project because of the economic ramifications. Alternative solutions were sought which would extend the lean limit and maximize gas utilization.

Objectives and Approach

The overall objectives of this study were to define the lean operating limit for a Bombardier dual-fuel locomotive engine and to determine methods by which the lean limit could be extended, given the hardware constraints of the Phase II project.

The following approach was used to achieve these objectives:

1. Literature was reviewed with regard to lean operating limits for dual-fuel diesel engines.
2. Literature was searched for cause-and-effect relationships between engine operating parameters and the lean limit, efficiency, power, and exhaust emissions.
3. Bombardier locomotive diesel engine performance data were reviewed and used to make and estimate of the lower notch operating limit.
4. The findings from the literature search were applied to propose methods by which the lean limit of a Bombardier engine could be extended.

A number of assumptions were made during the course of this project which affected the direction of study and the extent to which subjects were addressed. It is appropriate that these assumptions be mentioned before reviewing the results.

First, it was assumed that liquified natural gas (LNG) will be the fuel ultimately used in a dual-fuel locomotive. CNG may be used during research phases of the program, but LNG will ultimately be required if a locomotive is to achieve a reasonable operating range. The composition of LNG is very consistent, unlike CNG or pipeline natural gas, and therefore fuel property effects were not addressed in this study. Also, LNG can be used as a coolant (with considerable cooling capacity), which may have application for intake air temperature control.

Dual-fuel diesel engines are commonly required to operate both as a natural gas dual-fuel engine and as a conventional diesel engine. This decision results in design compromises to accommodate both modes of operation. The diesel fuel injection system is of concern in this study since a choice must be made between a system sized to provide adequate diesel fuel for full-power operation or a system which is considerably smaller for dedicated pilot diesel fuel injection. Dual-fuel engines are capable of operating with pilot quantities that are less than the idle fuel rate. An injection system sized for full-power operation does not have the turn-down ratio needed to meter such small quantities of fuel. It was assumed for this study that a dedicated pilot injection system would be available, resulting in accurate pilot fuel metering as well as good pilot injection spray quality.

The natural gas/air mixture was considered to be homogeneous in the combustion chamber. This constraint was imposed by the requirement that Bombardier dual-fuel engine hardware be used during Phase II. Gas is introduced into the intake port of the cylinder head using a valve arrangement which prohibits variable gas valve timing. The gas and air mix well as they pass through the intake valve and move about the cylinder. (An electronically actuated gas valve is being considered by Bombardier and Woodward Governor, but the availability of such a valve for Phase II application is uncertain.)

Finally, it was assumed that an engine conversion which made maximum use of stock Bombardier dual-fuel engine components would be most attractive for Phase II. This study was therefore directed to seek methods to extend the lean limit that can be implemented on a stock engine. More radical conversions are given mention in this report, but the thrust of the effort was directed towards options that use the stock head, piston, and valve actuating mechanism.

2. LEAN LIMIT FOR DUAL-FUEL OPERATION

The lean limit for dual-fuel operation of the diesel engine using either methane or natural gas is generally regarded as occurring at one of two thresholds: the limit for pilot diesel fuel ignition, and the lean flammability limit of the gaseous fuel. While both limitations are recognized in the literature, little attention has been focused on pilot combustion, even though it poses the more sensitive of the two limits. Such inattention to pilot combustion probably results from the fact that the vast majority of dual-fuel engines are used in stationary applications which spend the majority of their time operating at high power conditions. Typical remedies for poor pilot combustion are to increase the quantity of pilot or switch to 100 percent diesel fuel operation. Neither of these solutions are desirable for a locomotive application.

Ineffective pilot combustion at low power conditions results predominantly from intake air throttling, which reduces the effective compression ratio (2, 5). The majority of the references dealing with four-stroke engines consider throttling to be a requirement if reasonable efficiency and hydrocarbons emissions are to be achieved at low power conditions. The addition of a throttle plate to the inlet of a Bombardier turbocharged engine is undesirable because it adds complexity to the system and introduces throttling losses. The preferred method at the time of this report writing was to employ a wastegate on the turbocharger to control air consumption. Unfortunately, wastegating alone will not be adequate unless the lean limit for dual-fuel operation is set at a relatively high notch position, which will probably be at around 50 percent of full power. Restriction of air flow will be required below this point to reduce the mass of air admitted to the combustion chamber and maintain air fuel ratio within gas flammability limits.

The fuel/air ratio is expected to vary across the operating range of the engine as shown in Figure 1. The fuel/air ratio will be relatively rich at full power and will decrease with power until the lean limit is approached. Within this range, turbocharger wastegating will be an effective means of optimizing engine performance. Below a certain point on the notch schedule, throttling must be employed to maintain an fuel/air ratio which is slightly above the lean flammability limit. The fuel/air ratio will be essentially constant at this value beginning at the notch position where throttling must be initiated and terminating when the true lean limit of the engine is encountered. The true engine lean limit will occur when:

1. Throttling is so severe that the pilot combustion is weakened to the extent that it will not initiate gaseous fuel combustion.

2. The equivalence ratio has fallen below the lean flammability limit of the gaseous fuel.

3. The quantity of pilot fuel required for efficient combustion exceeds the amount of diesel fuel used in 100 percent diesel operation to achieve the same power output.

While the latter item sounds implausible, it is actually a case that is easily encountered. Such a situation can be expected at notches 2, 1 and idle for an unthrottled dual-fuel engine (7).

GAS FLAMMABILITY LIMIT

The lean flammability limit of methane or natural gas may be found in numerous references, but there is little agreement among the authors (1-6). Table 1 summarizes these findings. Lean limits were found to range from an equivalence ratio of 0.20 up to 0.53. The disparity among these values is the result of determinations being made with both combustion bombs and engines, spark ignition and pilot ignition, and with varying compression pressures, temperatures, and quantity of pilot diesel fuel. Zabetakis provides the most complete documentation of methane lean limit ignition (6). This Bureau of Mines report provides data showing that flammability limits are a function of air/fuel ratio, pressure, and temperature. Figures 2 and 3 show the effect of temperature and pressure on the lean flammability limit for methane. Temperature has a very strong effect on the flammability limit while pressure is a relatively weak variable. These findings are verified by Moore and Mitchell (1). Zabetakis developed a correlation for the lean flammability limit of methane as a function of temperature, which is as follows:

$$L_t = 5.0 -.0039(t-25)$$

where L_t is the volume percent methane flammability limit and t is temperature in degrees C

Flammability limits for three temperatures were calculated and are presented in Table 1. At room temperature, the lean limit is at an equivalence ratio of 0.50. The limit decreases to 0.37 at a temperature of 300°C. This temperature corresponds to the peak compression temperature using an inlet air temperature of 15.6°C (60°F) at an estimated effective compression ratio of 10.3 for the Bombardier 251 engine (mechanical compression ratio 11.5). If we assume that the intake air temperature is 82°C (180°F) as is common on an intercooled turbocharged engine, the peak compression temperature will be about 628°C which reduces the lean flammability limit to 0.26. This span of data easily covers the lean limits found in literature based on combustion bomb or engine tests.

Table 1

Lean Flammability Limits of Methane and Natural Gas in Air at Atmospheric Pressure

Author	Reference	Fuel	Temperature (°C)	Equivalence Ratio
Moore	1	Methane	15.6	0.531
Moore	1	Natural Gas	15.6	0.53 to 0.39
Song	2	Natural Gas	Unknown	0.40 to 0.50
Bro	3	Methane	Unknown	0.29 to 0.50
O'Neal	4	Methane	Unknown	0.40
Karim	5	Methane	Unknown	0.20
Zabetakis	6	Methane	25	0.50
Zabetakis	6	Methane	350	0.37
Zabetakis	6	Methane	628	0.26

It is possible to operate a dual-fuel diesel engine below the lean flammability limits reported by Zabetakis; such limits apply to sustained flame propagation of homogeneous gas-air mixtures. Pilot diesel fuel will initiate combustion of an overly lean gas-air mixture in the localized regions directly surrounding burning diesel fuel droplets (8). However, flame propagation will not be sustained and much of the gas will exit the cylinder unburned. High hydrocarbons (methane) emissions are a direct indicator of this problem. Increasing the quantity of pilot diesel fuel naturally reduces the hydrocarbon emissions, but thermal efficiency is typically quite poor unless flame propagation can be supported. Moore indicates that mixtures weaker than 0.1 equivalence ratio react only in the region of pilot ignition (1). An equivalence ratio of 0.5 or greater is required for reasonable hydrocarbons emissions according to Bro (3).

The lean flammability limit can also be surpassed by using swirl or turbulence to feed unburned gas into burning diesel fuel regions (1, 9). SEMT-Pielstick successfully employed swirl to improve combustion of a production dual-fuel medium-speed diesel engine, although there is no indication that the intention was to exceed the lean flammability limit (14).

Karim appears to have been the most aggressive in terms of exceeding the lean flammability limit for methane (5, 8, 10, 11). Engines operated at equivalence ratios down to 0.15 can be found in his papers. However, combustion at such extremes is poor as evidenced by the high hydrocarbons emissions. More reasonable emissions and efficiencies are reported above equivalence ratios of about 0.3.

A reasonable lean flammability limit for methane using a Bombardier engine with no attempts to increase swirl, turbulence, or intake temperature would be at an equivalence ratio of 0.4 as proposed by O'Neal (4). Employing increased air motion and inlet temperature will extend the flammability limit below 0.4, but it is not likely to exceed the value of 0.3 without more extensive modifications, which are the subject of Section 4 of this report.

PILOT IGNITION LIMIT

Imposition of a lean limit due to poor pilot fuel ignition was mentioned above. This subject deserves more discussion since it is likely to be a prime consideration if throttling is used on the Bombardier dual-fuel locomotive. An attempt was made to determine the operating conditions at which pilot ignition would fail in a Bombardier dual-fuel engine. The determination was unsuccessful as will be explained, but some observations made during the analysis are worth mentioning.

The limit for pilot fuel combustion was assumed, for this analysis, to occur when the compression pressure and temperature fell below minimum levels for autoignition of diesel fuel. Autoignition data were available for hydrocarbon lubricants through Bureau of Mines studies (12). Both compression pressure and temperature have a strong effect on the autoignition temperature.

Deterioration of pilot combustion characteristics results from intake throttling in combination with the advanced pilot injection timings. The pilot fuel must be injected and ignited before the air-gas mixture is fully compressed. Given that the compression pressure and temperature rises most rapidly during the final portion of the compression stroke, the pilot fuel with its advanced timings must ignite under conditions that are relatively poor compared to conventional diesel fuel. Throttling intake air further reduces compression pressure and temperature, accounting for the sensitivity of pilot ignition to throttling.

Throttling reduces both pressure and temperature as intake air passes across the throttling plate. However, it is important to consider the location of the intercooler on a turbocharged engine. Assuming that the engine is operating at a low power condition near the lean limit and that turbocharger boost pressure is minimal, the intake air will be heated to a temperature nearly equalling engine water temperature as it passes through the intercooler (13). Intercoolers, which are sized to provide cooling at full power conditions, have considerable capacity to heat the small amount of air consumed at low power conditions. Final compression temperature will not differ from that of an unthrottled engine; only intake air pressure will be affected by the throttling process. From the standpoint of lean limit operation, reheating the intake air after throttling is desirable and positioning the throttle plate upstream of the intercoolers is recommended.

Assuming that the throttling plate is located ahead of the intercoolers, compression pressure is the only factor which will affect pilot ignition due to intake air throttling. Compression temperature at top dead center will be about 630°C for an inlet air temperature of 82°C (180°F) and an effective compression ratio of 10.3. Data contained in Reference 6 show this to be above the autoignition temperature for diesel fuel at atmospheric pressure. Reference 12 indicates that the autoignition temperature will be still lower at elevated pressures. These Bureau of Mines reports predict that pilot diesel fuel will auto-ignite at the above compression ratio and intake air temperature regardless of the degree of throttling. However, engine test data clearly indicate that throttling has a pronounced effect on pilot ignition and misfiring can occur. Therefore, it must be concluded that autoignition temperature of diesel fuel is not a good predictor of pilot misfire.

Further investigation of the test procedures by which autoignition temperatures were measured revealed that extremely long ignition delays, measured in seconds, were prevalent during these tests (12). Pilot diesel fuel ignition delays on the order of a few milliseconds will be required in a dual-fuel diesel engine. Temperatures well above autoignition temperatures must be reached before such short ignition delays are achieved. A correlation between diesel fuel ignition delay and both pressure and temperature will be needed to make and accurate prediction of pilot diesel fuel behavior. Pressure and temperatures encountered in a diesel engine were well beyond the range of data presented in Reference 12. Determination of pilot ignition characteristics is best handled experimentally. The ignition characteristics are very engine dependent, with a large number of variables at work. The single-cylinder Bombardier 251 engine would be ideal for the study due to the external control of intake pressure and temperature. Care should be taken to operate using a main fuel charge of methane or natural gas when studying pilot ignition. Combustion of the main charge has a pronounced effect on pilot combustion during the following cycle (16).

EFFECT OF OPERATING VARIABLES ON PERFORMANCE

Researchers have conducted parametric studies concerning the effects of engine operating variables on dual-fuel performance. The variables are interrelated such that a closed form solution to the dual-fuel engine design problem does not exist. The following sections present a synopsis of the cause-and-effect relationship between operating variables and performance. Exhaust emissions will be discussed in Section 5.

Engine Load

The minimum load or power output at which gaseous fuel can be consumed is a common rating for dual-fuel engines. Pielstick, for example, cites a 30 percent load as the lean limit for a medium-speed dual fuel engine (14). Unfortunately, load is a very general term and does not describe the combination of operating variables that impose the lean limit. It is recommended that load limits not be used to determine the lean limit of the Bombardier engine.

Pilot Quantity

It is desirable to minimize the pilot fuel quantity during dual-fuel operation to maximize use of less expensive gaseous fuel. However, if pilot quantity is reduced below its optimum amount, ignition of gaseous fuel will be weak resulting in poor thermal efficiency and high hydrocarbons emissions (4, 9). Pilot quantity varies inversely with fuel-air ratio. Leaner mixtures will require a stronger ignition source and therefore more pilot diesel fuel. The increased fuel quantity provides more ignition points within the cylinder and generally increases the cylinder temperature, improving gas flammability and increasing flame speed. Richer mixtures are more easily ignited and naturally require less pilot diesel fuel.

Stated differently, the lean fuel/air ratio limit increases as the amount of pilot fuel decreases. Therefore, attempts to use an overly small amount of pilot may result in a relatively high lean limit, forcing the switch-over point (the point at which operation must switch from dual-fuel to 100 percent diesel) to be at a relatively high notch position.

Fuel-Air Ratio

Fuel-air ratio is the predominant variable to be considered as the lean limit is approached. The effect of gaseous fuel-air ratio on flame speed is commonly known, but an additional factor is its effect on pilot combustion (1, 3, 5, 8, 10, 11). Figure 4 shows the relationship between equivalence ratio and pilot ignition delay. The ignition delay of the pilot increases considerably on addition of the gaseous fuel, up to an equivalence ratio of 0.3, then reduces with further gas addition. Unfortunately, ignition delay is at a maximum in the very region (0.3 to 0.4 equivalence ratio) which is expected to be the lean limit. Steps can be taken to shorten the ignition delay, which include elevating intake air temperature, increasing compression ratio, and use of a high cetane diesel fuel.

Flame speed is shown as a function of equivalence ratio and mixture temperature in Figure 5 (10). Flame speed reaches a maximum at equivalence ratios slightly to the rich side of stoichiometric. Flame speed decreases rapidly as the mixture becomes leaner. Unfortunately, data were not available near the lean limit. An overly slow flame speed will ultimately result in poor efficiency due to late burning in the cycle or failure of the flame to propagate. Flame speed is a function of mixture temperature as indicated in Figure 6. The data shown are for a temperature range well below that found near top dead center on a compression stroke. Flame speed reaches a maximum of 0.45 m/s at about 280°K (7°C) and is essentially constant above this temperature. Therefore, gas temperature does not appear to influence flame propagation for the operating temperatures expected in the Bombardier dual-fuel engine.

Compression Ratio

Compression ratio is an important design variable for a dual-fuel engine since it impacts knock limited operation, lean limited operation, and cold-starting (4). A high compression ratio is desirable to extend the lean limit. The elevated pressures and temperatures are beneficial from the standpoint of pilot ignition and gaseous fuel lean flammability limit. However, a low compression ratio is desirable in the case of the Bombardier dual-fuel locomotive *to achieve full diesel power rating and to reduce friction horsepower.* Cold starting is frequently the ultimate determinant of compression ratio in a dual-fuel engine. That may be especially true for a rail engine which will not have the luxury of starting aids or a heated engine room such as exists in stationary applications. The compression ratio selected will be a compromise and must be determined empirically.

Intake Temperature

Aside from fuel-air ratio, intake air temperature is probably the most influential operating variable near the lean limit. This is advantageous since temperature can be easily controlled with heat and cooling sources that readily available on a locomotive. Heat is, of course, provided by engine cooling water or possibly exhaust gas. Cooling will be available through vaporization of LNG. Temperature influences both the knock limit and the lean limit. Pilot and gas ignition improve with temperature, which is desirable at the lean limit (but undesirable at the knock limit). Figure 7 shows the effect of inlet air temperature on ignition delay in a CFR engine. The temperature effect is quite pronounced and appears to be an attractive means of offsetting the increased ignition delay resulting from interactions between the gaseous fuel and pilot. Song and Hill concluded that increasing intake temperature was the only practical way to extend the lean limit (2), although some additional techniques are proposed in section 4.

The relationship between mixture temperature and the lean flammability limit of methane is shown in Figure 8. It should be noted that the temperature of concern for natural gas is the mixture temperature in the combustion chamber at the time of gas ignition. This temperature will be a function of the compression ratio, inlet air temperature, and pilot combustion. The appropriate combination of these three factors will produce mixture temperatures above the lean limit which will sustain flame propagation. Below the lean limit, localized burning of gas near diesel fuel droplets may occur, but flame fronts will be extinguished as they move into the cold surrounding gases.

Reference 8, written by Karim and Burn, focuses on intake temperature effects with emphasis placed on cold conditions. The effect of inlet temperatures on pilot combustion, equivalence ratio requirements, performance and emissions are documented. Review of this reference is recommended if intake air temperature control is selected as a means of influencing combustion.

Intake Pressure

Intake air pressure has little effect on methane flammability as shown in Figure 3 at the lean limit (although the rich limit is rather dramatically affected) (1, 6). However, a reduction in intake air pressure due to throttling can have an adverse affect on pilot ignition delay as shown in Figure 8 (15). The variations in ignition delay shown occurred at constant inlet air temperature which is analogous to the case discussed previously for an intercooled diesel engine.

Swirl and Turbulence

Tesarek postulated that swirl was an important parameter near the lean air-gas ratio limit (9). If a flame is unable to propagate in a quiescent chamber, swirl will bring unburned mixture into locations near pilot fuel droplets where combustion is underway. This technique will be most successful with a long pilot fuel injection duration.

Moore cites a case in which turbulence reduced the lean limit from 5.6 to 5.0 percent (1). His work must have been conducted in a bomb as the turbulence was generated by a fan. Nonetheless, the concept of moving unburned mixture into regions of combustion appears viable.

Surface Temperature

Karim investigated quenching and found a strong relationship between mixture temperature, equivalence ratio, and quench distance (10). The data from this work are presented in Figure 9. Minimum quenching was found with mixtures near stoichiometric. The quenching distance increased rapidly as the mixture was made either too lean or too rich. Quenching distance refers to the distance from the bomb surface to the end of flame propagation. Karim also found that quenching distance increased almost linearly as the gas mixture temperature decreased. At low temperatures, quenching resulted in a large amount of unburned fuel, which would produce high hydrocarbons emissions and poor efficiency in a diesel engine (5). Quenching in a diesel engine will be affected by both the mixture temperature and combustion chamber surface temperatures. Increases in both temperatures are desirable near the lean limit to minimize quenching.

From the above discussions, it is apparent that the lean limit for a dual-fuel engine is a function of many interrelated variables. As such, the lean limit will be highly engine-dependent. An accurate prediction of the degree to which the lean limit can be extended beyond an equivalence ratio of about 0.4 is not possible. Experimental studies are recommended to determine the most appropriate limit for a dual-fuel Bombardier locomotive.

Steps that can be taken to extend the lean limit to the greatest extent are:

- Select the highest possible compression ratio as allowed by full power knocking;
- Minimize throttling losses by using the leanest fuel-air ratio at which the gas will burn efficiently;
- Elevate intake air temperature at low power settings;
- Use a high cetane number pilot fuel;
- Increase turbulence and/or swirl; and
- Employ a dedicated pilot injection system and carefully optimize spray geometry and timing.

3. BOMBARDIER 251 ENGINE LEAN LIMIT

An estimate was made of the air/fuel ratio for a Bombardier 251 dual-fuel engine for the purpose of determining the lowest Notch position that could be run without intake air throttling. No attempt was made to predict the lean limit when throttling the intake due to the uncertainty of the impact of throttling on pilot diesel fuel ignition (see Section 2).

Data were provided by Bombardier which were the basis for the calculations. The measurements were made at Bombardier using a 12 cylinder 251 diesel engine and are presented in Table 2. A 12.5 compression ratio was run in this engine, which differs from the planned 11.5 for the dual-fuel engine. However, when considering the nature of the lean limit estimates and the assumptions that were made, the difference in compression ratio was felt to be of minor importance. Engine data were converted from SI to English units as shown in Table 2.

The procedure for estimating air/fuel ratio was as follows:

1. Estimate trapped air volume;
2. Estimate mass of methane consumed;
3. Calculate the volume occupied by methane in the combustion chamber, and subtract this volume from the air volume;
4. Calculate the mass of air;
5. Calculate air/fuel ratio and equivalence ratio.

Of course, it was necessary to make a number of assumptions to bridge gaps where data were lacking. Each of the steps in the procedure is reviewed below and the assumptions are presented.

The trapped air volume was calculated based on air mass consumption measured by Bombardier. The calculations are shown in Table 3. An estimate was made of the volumetric efficiency using formulas suggested by Taylor (19). However, volumetric efficiency does not adequately describe the situation for a turbocharged engine with a long valve overlap. Air flows through the cylinder and exits the exhaust when intake pressure exceeds exhaust back pressure. An additional term, known as trapping efficiency, must be included. Reference 20 contains a trapping efficiency estimate of 0.85 for the 251 engine at full power. Taylor presents data showing that trapping efficiency goes to a value of 1 when intake pressure equals exhaust back pressure (19). Boost pressure is negligible at Notches 1 through 5; as a result, a trapping efficiency of 1 was assigned to these notches. Trapping efficiencies were arbitrarily assigned at Notches 6 and 7, and ranged between the values at Notches 5 and 8 as shown in Table 3. Volumetric efficiency was multiplied by trapping efficiency to calculate "trapped volumetric efficiency", which was then used to estimate trapped air mass. Trapped air represents the mass of air that resides in the cylinder after the valves close.

Table 3 also presents a trapped air volume. This number is the volume that the trapped air mass would occupy at a pressure and temperature equal to inlet air conditions. The trapped air volume should be equal to or less than the cylinder displacement of 671 in^3, the difference being exhaust residual fraction. Notches 6 to 8 had an estimated residual fraction of about 15 percent of the cylinder volume. The calculation for Notch 5 shows an air volume exceeding cylinder volume. Considering that there is negligible intake boost pressure at Notch 5, this result is unreasonable. An error in the air mass consumption or boost pressure data is suspected to be the cause.

Methane consumption rates were calculated assuming that thermal efficiency of the dual-fuel engine equalled that of the 251 diesel engine as shown in Table 2. Also, the pilot diesel fuel input was assumed to be 10 percent of the combined diesel and methane BTU input at each notch position. Given thermal efficiency and pilot diesel fuel data, the mass of methane needed to produce the same brake horsepowers as a diesel locomotive was calculated. The results are presented in Table 4. The volume occupied by methane in the cylinder at a pressure and temperature equal to inlet air conditions was then calculated, and the volume of air was reduced by the same amount. Finally, air mass was determined based on the reduced air volume as shown in Table 4.

Equivalence ratio is also presented in Table 4. The estimates were somewhat low for the uppermost notches, especially at Notch 8 where an equivalence ratio approaching stoichiometric was expected. By contrast, low numbered notches were estimated to have high equivalence ratios with Notch 1 being the only position below the lean limit.

The equivalence ratios presented in Table 4 are not reasonable when compared to the wealth of data available in literature. Examining the calculation procedure, the method used to calculate trapped air mass was found to be questionable for low notch positions. The trapped air volume was estimated to be only about 50 percent of the cylinder volume at Notches 1, 2 and 3, with the balance being exhaust residual. As a result, the equivalence ratio calculated in Table 4 was based on the mass of fresh air inducted into the cylinder each stroke, ignoring the exhaust residual and the air it contains.

A second estimate of equivalence ratio was made based on the combined fresh air charge and exhaust residual. A cylinder was assumed to contain 602.6 in^3 of air (the cylinder volume at intake valve closing). The mass of air was calculated based on this volume minus the volume occupied by methane. The results are presented in Table 5. Equivalence ratios at Notches 1 to 5 are in the ranges predicted by literature.

The lean limit below which intake air throttling will probably be required is Notch 4 (see Table 5). Notch 3 is estimated to have an equivalence ratio of 0.38, which is below the expected lean limit of 0.4 by only a small margin. Implementation of the techniques described in Sections 2 and 4 to extend the lean limit may make unthrottled operation at Notch 3 possible. The low equivalence ratio of 0.28 at Notch 2 will be difficult to overcome. Throttling will surely be needed at Notch 2 to reach an acceptable equivalence ratio, but poor pilot ignition when throttling may lead to poor performance. It is doubtful that Notch 2 will be acceptable in dual-fuel operation unless extreme measures such as are suggested in Section 4 are implemented.

Table 5 also shows the equivalence ratio at Notches 6 to 8. Again, the values appear to be low, especially at Notch 8. Reviewing the data in Table 5, it appears that the mass of air is high due to the high boost pressures at these conditions, resulting in lean fuel/air ratios. Boost pressure was assumed to be the same as a conventional diesel engine. Such high pressures will probably not be achieved in a dual-fuel engine because of limits imposed by exhaust temperatures at the turbine inlet. Since the focus of this report was the lean limit, no attempt was made to correct the data at the upper notches.

Table 2
Bombardier Locomotive Diesel Engine Data

12 cylinder 251 engine
12.5 compression ratio

Notch	RPM	BHP	BMEP (bar)	Air Flow (kg/sec)	Air Temp (C)	Air Pres (kPa)	Fuel Flow (kg/hr)	BSFC (gm/kwh)	Thermal Effic.
8	1100	2200	13.62	2.725	88.0	255.00	359.7	219.4	0.392
7	1000	1649	11.25	2.004	79.7	197.00	273.2	222.0	0.387
6	900	1203	9.10	1.392	75.6	152.00	204.2	227.5	0.378
5	800	844	7.20	0.944	75.0	101.48	148.7	236.0	0.364
4	700	565	5.51	0.603	75.0	101.46	103.0	244.7	0.352
3	600	356	4.05	0.373	75.0	101.46	67.7	254.5	0.337
2	500	205	2.80	0.282	74.0	101.00	41.5	270.5	0.318
1	400	103	1.76	0.230	74.5	99.00	23.2	300.0	0.286

Notch	RPM	BHP	(psi)	(lb/sec)	(F)	(psia)	(lb/hr)	(lb/BHP-h)	Effic.
8	1100	2200	197.5	6.009	190.4	36.98	793.1	0.361	0.392
7	1000	1649	163.1	4.419	175.5	28.57	602.4	0.365	0.387
6	900	1203	132.0	3.069	168.1	22.04	450.3	0.374	0.378
5	800	844	104.4	2.082	167.0	14.72	327.9	0.388	0.364
4	700	565	79.9	1.330	167.0	14.72	227.1	0.402	0.352
3	600	356	58.7	0.822	167.0	14.72	149.3	0.418	0.337
2	500	205	40.6	0.622	165.2	14.65	91.5	0.444	0.318
1	400	103	25.5	0.507	166.1	14.36	51.2	0.493	0.286

Table 3
Trapped Air Volume and Mass

Notch	Air Flow (lb/sec)	Volumetric Efficiency	Trap Effic.	Trapped Volumetric Efficiency	Trapped Air Flow (lb/sec)	Trapped Air Mass (lb/cyl)	Trapped Air Volume (in3/cyl)
8	6.009	0.92	0.85	0.78	5.107	0.0464	522.6
7	4.419	0.94	0.90	0.84	3.977	0.0398	566.2
6	3.069	0.93	0.95	0.88	2.916	0.0324	590.8
5	2.082	1.06	1	1.06	2.082	0.0260	709.5
4	1.330	0.77	1	0.77	1.330	0.0190	518.0
3	0.822	0.56	1	0.56	0.822	0.0137	373.9
2	0.622	0.51	1	0.51	0.622	0.0124	339.7
1	0.507	0.53	1	0.53	0.507	0.0127	353.9

Table 4
Equivalence Ratio Based on Measured Air Consumption Rate

Notch	Trapped Air Mass (lb/cyl)	Trapped Air Volume (in3/cyl)	Methane Mass Flow (lb/sec)	Methane Mass (lb/cyl)	Methane Volume (in3/cyl)	Trapped Air less Methane (in3/cyl)	Trapped Air less Methane (lb/cyl)	Air/Fuel Ratio (lb/lb)	Equiv. Ratio
8	0.0464	522.6	0.150	0.00136	27.69	495.0	0.0440	32.3	0.53
7	0.0398	566.2	0.114	0.00114	29.25	536.9	0.0377	33.2	0.52
6	0.0324	590.8	0.085	0.00094	31.10	559.7	0.0307	32.5	0.53
5	0.0260	709.5	0.062	0.00077	38.11	671.4	0.0246	31.8	0.54
4	0.0190	518.0	0.043	0.00061	30.16	487.9	0.0179	29.2	0.59
3	0.0137	373.9	0.028	0.00047	23.15	350.7	0.0129	27.4	0.63
2	0.0124	339.7	0.017	0.00034	16.98	322.8	0.0118	34.3	0.50
1	0.0127	353.9	0.010	0.00024	12.12	341.8	0.0122	50.9	0.34

Table 5
Equivalence Ratio Based on a Constant Trapped Air Volume

Notch	Trapped Air Volume (in3/cyl)	Methane Mass Flow (lb/sec)	Methane Mass (lb/cyl)	Methane Volume (in3/cyl)	Trapped Air less Methane (in3/cyl)	Trapped Air less Methane (lb/cyl)	Air/Fuel Ratio (lb/lb)	Equiv. Ratio
8	602.6	0.150	0.00136	27.69	574.9	0.0511	37.5	0.46
7	602.6	0.114	0.00114	29.25	573.4	0.0403	35.4	0.49
6	602.6	0.085	0.00094	31.10	571.5	0.0313	33.2	0.52
5	602.6	0.062	0.00077	38.11	564.5	0.0207	26.8	0.64
4	602.6	0.043	0.00061	30.16	572.4	0.0210	34.3	0.50
3	602.6	0.028	0.00047	23.15	579.4	0.0212	45.2	0.38
2	602.6	0.017	0.00034	16.98	585.6	0.0214	62.3	0.28
1	602.6	0.010	0.00024	12.12	590.5	0.0212	88.0	0.20

4. METHODS TO EXTEND LEAN LIMIT

The purpose of this section is to propose some alternative methods by which the lean limit of a dual-fuel engine might be extended. The ideas put forth here stray from conventional practices as described in Section 2. The steps normally taken to improve low power performance or extent the lean limit are (2,5):

1. Use of a larger quantity of pilot fuel;
2. Use of advanced pilot injection timings;
3. Use of lowest possible injection nozzle opening pressure (applies to injection systems that handle both pilot and main fuel);
4. Restricting intake air;
5. Preheating intake air.

All of the above steps should be evaluated, preferably in the laboratory, using a Bombardier dual-fuel engine. As mentioned in Section 1, use of a larger quantity of pilot diesel fuel is undesirable from a gas-utilization standpoint, but it may be necessary in the final analysis of performance trade-offs.

Alternative methods which may be applied to extend the lean limit of a dual-fuel locomotive are:

1. Stratified gas charge,
2. High compression ratio/intake air temperature control,
3. Exhaust gas recirculation (EGR),
4. Direct high pressure gas injection.

The first three techniques are potential candidates for either Phase II or III work, while the fourth could only be considered for Phase III. Each of these four techniques is outlined below.

Stratified Gas Charge

The lean flammability limit of methane poses the most significant barrier to lean limit operation. Thermal efficiency decreases and hydrocarbon emissions increase significantly once the gas-air mixture becomes too lean to support flame propagation. Methane is consumed in regions close to burning pilot diesel fuel droplets of overlean mixtures, but the remaining fuel is expelled unburned. Increased swirl, turbulence and pilot quantity will increase the amount of gas that reaches burning pilot fuel.

Stratifying the gas charge may improve gas combustion at fuel-air ratios near to or beyond the lean gas flammability limit. A heterogeneous gas-air mixture will contain regions of rich as well as lean mixtures. Flames will propagate in those regions whose mixtures are above the lean flammability limit. A well distributed pilot diesel fuel charge will ignite many such regions, consuming more gas than with a homogeneous charge.

The effectiveness of a stratified charge concept depends on the pilot reaching a large percentage of the rich gas-air mixture regions in the combustion chamber. Unfortunately, it follows that larger pilot quantities or longer injection durations will encompass a larger volume of the combustion chamber and therefore will be more effective. Stratifying systems that introduce the gas into the intake system will face this situation because of the random orientation of rich regions throughout the combustion chamber.

Stratification can be improved by introducing the gas directly into the combustion chamber. Placement of the gas near the cylinder centerline of a low swirl/low turbulence engine during the intake or compression strokes will result in a rich zone near the cylinder center and little gas near the perimeter. Such placement is ideal for minimizing pilot diesel fuel requirements. The drawback to direct cylinder gas admission is the addition of another valve to the cylinder head to handle the gas. Furthermore, while a stratified charge is beneficial for extending the lean limit, it is detrimental at full power where a well mixed gas-air charge is needed. Some means must be included to vary gas-air mixing, such as variable swirl intake systems now appearing on the automotive and motorcycle markets.

Stratified charge concepts may be attractive as an alternative to intake air throttling, or as a means to reduce the amount of throttling. Thus, in addition to extending the lean limit, pumping losses could be reduced.

Stratifying the gas is a consideration for Phase II. Variable gas valve timing or a ducted intake port are possible stratifying approaches that could be implemented using existing dual-fuel heads. Direct cylinder admission will require head redesign and the additional of a valve actuating system, which are beyond the scope of the Phase II program.

High Compression Ratio/Intake Air Temperature Control

The compression ratio of a dual-fuel engine is selected to avoid knock at full power, yet allow the engine to start in cold conditions. The compression ratio is usually below that of a conventional diesel engine. Throttling intake air further reduces the effective compression ratio at low power. The low compression temperatures and pressures that result have an adverse effect on pilot ignition and the lean flammability limit of methane.

A high compression ratio is attractive at the lean limit of operation and for starting. A relatively high effective compression ratio can be maintained in spite of throttling losses to improve pilot ignition. Elevated cycle temperatures decrease the flammability limit of the gas. However, knock limited power decreases significantly as compression ratio increases, as shown in Figure 10. An option is available for an LNG fueled engine to control knock while operating at a high compression ratio. That option is to cool the intake air charge. Considerable cooling capacity is available because of the amount of energy required to vaporize LNG from its storage temperature of -128°C (-260°F).

Figure 11 shows the effect of intake air temperature on knock (5). This same reference provides a correlation between peak cycle temperature and knock-limited BMEP as shown in Figure 12. Thermodynamic calculations for an idealized cycle can be made to estimate the knock limited compression ratio over a range of intake temperatures. Such calculations are a subject for consideration in the Phase II program. Included in this study should be estimation of the maximum cooling available at full power output.

Cooling of the intake charge will be detrimental at operating conditions that are not prone to knocking. In particular, low power conditions should operate with the highest possible intake air temperature. Therefore, the intake system must be capable of cooling or heating the air as needed.

A major attraction to the High Compression Ratio/ Intake Air Temperature Control concept is the ease with which it can be implemented on an LNG locomotive. An unmodified Bombardier dual-fuel engine can be used, aside from the installation of higher compression ratio pistons. The temperature controls are largely external to the engine and are relatively unsophisticated. This technique appears to be a candidate for Phase II study.

Exhaust Gas Recirculation (EGR)

EGR is a commonly employed method of controlling emissions. A portion of the exhaust is directed into the intake system, displacing air with a largely inert gas. Tesarek studied EGR in gas engines for emissions control(9). The maximum amount to EGR was limited by engine misfire to 45 percent. The emissions benefits were considerable.

EGR may have application to the dual-fuel locomotive, not for emissions control per se, but for possible elimination of throttling at low power conditions. The idea is simply to use exhaust gas to reduce the mass of air ingested each cycle, thereby maintaining a richer fuel-air ratio. Tesarek did not examine the impact of EGR at the lean limit, although he showed improvements in BSFC at all fuel-air ratios tested. Whether EGR can replace throttling is not known. However, the potential benefits of EGR make the concept worthy of further study. The benefits include:

1. Increased intake charge temperature,
2. Elimination of throttling losses,
3. Elimination of loss in effective compression ratio due to throttling,
4. Easily adaptable to stock dual-fuel engine,
5. EGR flow can be controlled by the Woodward 501,
6. Low exhaust emissions.

EGR fits well with Bombardier's plans to use an oxygen sensor in the exhaust to provide a feedback signal to a Woodward 501 controller.

Direct High Pressure Gas Injection

The ultimate means to control combustion of a dual-fuel engine is to inject the gas under high pressure late in the compression stroke. The combustion process closely resembles that of a conventional diesel engine. The gas is injected following pilot diesel injection, with the gas injection rate controlling combustion rate (17,18).

The single greatest hurdle facing this concept is generation of the high pressures required for gas injection. MHI employed a large gas compressor while Wakenell used a liquid pump prior to vaporization(17,18). Either of these pumping arrangements would add a considerable amount of complexity to an LNG locomotive. Other barriers include development of a gas injection system and safety issues concerning a high pressure gas system. However, the attractions to direct gas injection are very high gas utilization and elimination of knock and lean limits. MHI was able to operate on 1% pilot at some conditions and idle in a dual-fuel mode.

Direct high pressure gas injection is at one extreme of possible dual-fuel configurations, while carburetion of a homogeneous charge is at the other extreme. Stratified charge concepts lie in the range between these extremes. A trade-off exists between complexity and cost of each concept. Direct high pressure injection is a high-risk proposition and is well beyond the scope of Phase II of the program.

5. EXHAUST EMISSIONS

The purpose of this section is to provide an overview of the emissions levels that can be expected from a dual-fuel gas engine. While emissions are not regulated for locomotive engines at this time, the enviornmental impact cannot be ignored and steps should be taken to minimize emissions. EPA has studied emissions from rail and marine medium-speed diesel engines, but has not imposed regulations because of the low levels of regulated emissions produced by these engines and the relatively small number of engines. Locomotive engine builders are in a unique position of potentially avoiding regulation by producing clean burning engines.

An added incentive for studying emissions from a dual-fuel engine is the considerable amount of diagnostic information these measurements provide concerning combustion. The following sections address carbon monoxide (CO), oxides of nitrogen (NOx), hydrocarbons or methane (HC), and smoke emissions, with emphasis placed on the lean limit. The absolute value of the emissions presented should not be construed as being indicative of a Bombardier 251 dual-fuel engine; the majority of the data were acquired from smaller engines which are not representative of a medium-speed diesel. Emphasis should be placed on the effect of design and operating variables on emissions levels. This type of information will be of great value during the engine development process.

The focus of this section is the dual-fuel engine, but brief comments are included describing the emissions that can be expected from a dual-fuel engine operated in a 100 percent diesel mode.

DUAL-FUEL ENGINE EXHAUST EMISSIONS

Figure 13 shows the emissions from a dual-fuel engine compared to a conventional diesel engine (4). CO and HC levels are many times higher for the dual-fuel engine at low power output, especially near the lean limit. NOx levels are quite low at low power but increase with fuel/air ratio to levels that may be three times higher than a diesel engine at full power. NOx is the primary concern at full power, although HC and CO may be above diesel levels. By contrast HC and CO are of greatest interest at the lean limit.

Hydrocarbons Emissions

The general trend in HC emissions is shown in Figure 13.

These data are presented in units of concentration (ppm). HC data are perhaps more informative when converted to percent methane unreacted (unburned). Figures 14 and 15, obtained from Reference 8, shows the concentration of unreacted fuel as a function of equivalence ratio. Also shown are the effect of pilot quantity and inlet temperature. Inducting small quantities of methane below the lean limit results in expulsion of most of the gas unreacted. The concentration of hydrocarbons in the exhaust increase with added methane up to equivalence ratios of about 0.4 beyond which hydrocarbons decrease. This would appear to be the equivalence ratio at which flames begin to fully propogate throughout the combustion chamber.

Further evidence of the lean flammability limit can be seen in the sensitivity of HC emissions to inlet air temperature and pilot quantity in Figures 12 and 13. At equivalence ratios below 0.4, HC emissions vary considerably, increasing as inlet temperature or pilot quantity decrease. Elevated inlet temperatures or large amounts of pilot fuel are required to burn a significant percentage of methane below the lean gas flammability limit. However, above an equivalence ratio or about 0.4, HC is not strongly influenced by inlet temperature. Equivalence ratio becomes the controlling variable, with pilot quantity being of secondary importance. Interestingly, it appears that small quantities of pilot are desirable at equivalence ratios above 0.5 to minimize HC emissions.

The above discussions do not consider the effects of swirl and turbulence on HC emissions. Air motion is expected to improve combustion efficiency at or below the lean limit, although no data were avaiable to support this hypothesis.

EGR was found to be useful to reduce dual-fuel engine emissions (9). Hydrocarbons decreased by up to 30 percent using up to 45 percent exhaust recirculation, with the amount of reduction depending on the quantity of gas consumed.

Carbon Monoxide Emissions

Carbon monoxide is also a useful tool for analyzing combustion in a dual-fuel engine. High CO can be expected at low power, and especially when at conditions where flames will not propogate. Figure 13 shows the general trend in CO emissions across the power range of the engine. Figure 16 presents CO data as a function of equivalence ratio. The trends closely match HC emissions. CO reaches a maximun at the gas lean limit, about 0.4 in Figure 16, and decreases at higher equivalence ratios. High CO associated with overlean mixtures is the direct result of quenching in the gas-air mixtures surrounding ignition foci (5). Increased flame propogation tends to achieve more complete oxidation, explaining the low CO at high power.

Variables that impact CO include intake temperature, compression ratio, pilot quantity, and fuel-air ratio. An increase in any of these items will reduce CO emissions, although undesirable increases in NOx and knock will occur at high power outputs. Throttling was also found to reduce CO (and HC), but the improvements were directly attributable to enhanced combustion at increased fuel-air ratios (9). EGR was also beneficial, reducing brake specific CO by up to 50 percent (9).

NOx Emissions

NOx emissions are of greatest concern at high loads as shown in Figure 13. These high values stem from the higher fuel air ratios of a dual fuel engine compared to a diesel, which produce higher combustion temperatures (4). By contrast, low load operation generates very low levels of NOx.

The effect of equivalence ratio and pilot quantity are shown in Figure 17. Because NOx formation depends of temperature and oxygen, variations in combustion rate are readily evident. A rapid increase in NOx occurs once the lean gas flammability limit has been exceeded. Figure 17 also indicates that lean mixture combustion rates are considerably higher at high pilot fuel rates, verifying that increased pilot rate will extend the lean limit.

Measures that will reduce NOx emissions include any techniques that reduce peak combustion temperature and slow combustion rates. Examples of such measures are reduced compression ratio, reduced intake air temperature, reduced bmep, retarded injection timing, and EGR. Unfortunately, most of these measures compromise full power output. Cooling the intake charge may be the most attractive for an LNG locomotive since power output is not compromised and a large cooling source (vaporization of LNG) is available.

Exhaust Smoke

Dual-fuel engines have long been renown for their low exhaust smoke levels. Low soot formation also means clean combustion chambers and exhaust system, and low soot loading of lube oil. Tesarek documented smoke levels of less than half that of a diesel engine at maximum BMEP (9). Still greater reductions were shown at reduced BMEPs. The amount of pilot diesel injected will have a direct bearing on smoke emissions. If full power and engine accelerations can be achieved with small amounts of pilot, smoke levels will be very low.

EMISSIONS FROM A DUAL-FUEL ENGINE OPERATED ON DIESEL FUEL

O'Neal provides a good summary of the emissions levels that can be expected from a dual-fuel engine that is operated entirely on diesel fuel (4). The following discussion is drawn from his paper.

In general, black smoke will be somewhat lower for a dual-fuel engine. This is attributed to the reduced compression ratio in comparison to a conventional diesel engine. White or blue smoke tends to be higher during starting and warmp-up. However, since Bombardier plans to use an 11.5 compression ratio as is standard on 251 engines, changes in smoke are expected to be small and will result from altered valve timing, injection timing and injection spray characteristics.

Hydrocarbons and CO are usually reported to increase while NOx decreases in diesel operation of a dual-fuel engine relative to a conventional diesel engine. Again, these changes are credited to reduced compression ratio, which will not be the case for Bombardier. Therefore, emissions from a Bombardier dual-fuel locomotive operated on diesel fuel are expected to be nearly the same as a conventional diesel, with small changes possible due to differences in injection systems, valve timing or other operating variables.

6. GENERAL CONSIDERATIONS FOR LNG FUELING OF A LOCOMOTIVE

LNG handling and storage pose an entirely new set of requirements for hardware and safety as compared to diesel fuel. The railroads are accustomed to the rather lenient precautions used with diesel fuel. By contrast, considerable attention must be paid to safety when handling LNG or methane. Personnel must be trained in the use of cryogenic systems which, unlike diesel systems, need close monitoring. The purpose of this section is to introduce in general terms the considerations that must be given to an LNG tender and fuel system.

The heart of an LNG system is the cryogenic storage tank. It is essentially a large thermos bottle. Cryogenic tanks are frequently double wall vacuum jacketed tanks. Methane boils at a temperature of -161.5°C (-258.7°F) at atmospheric pressure. The critical temperature is -82.6°C (-116.7°F) above which the fluid is a vapor at any pressure. Cryogenic tanks have pressure ratings of up to several hundred psi. This rating is the maximum internal working pressure of the tank and, therefore, is the maximum pressure that can be applied to the liquid in storage. Pressures in this range make only minor differences in boiling temperature; consequently, the storage temperature can be considered to be -161.5°C.

Cryogenic tanks do not employ a refrigeration cycle to maintain temperature. In fact, there are no active pumping circuits and no power is required. Cooling is accomplished by boiling a portion of the liquid, with heat being absorbed during the vaporization process. The tank must be vented or pressure will build as heat transfers from the surroundings through the tank insulation. A hand valve is commonly used to control the rate of venting. A very low pressure can be maintained by fully opening the valve. Conversely, tank pressure will increase if venting is restricted, but the tank must be monitored to insure that pressure remains below the tank rating. A pressure gage mounted on the tank is a common means of measuring internal pressure. Cryogenic tanks typically have triple protection in case of overpressure in the form of two pressure relief valves and, as a last resort, a rupture disk. If any of these safeties activates, the tank is vented to atmosphere and a large amount of vapor and liquid can be expelled.

The piping network on a cryogenic tank is quite complicated, with about six hand valves controlling filling, venting and recirculation. Adjustment of these valves is somewhat complicated and multiple combinations of valve settings can achieve a desired result. However, improper valve settings can have serious consequences. Adjustment of a cryogenic tank should be handled only by an individual who has been properly trained.

Filling of a cryogenic tank also requires an experienced individual. Top and bottom fill lines are used. Part of the liquid is top filled. This liquid boils as it falls, cooling the tank. The remainder of the liquid is bottom filled. The proportions that flow to the top and bottom vary as the tank level increases since less cooling is needed during the latter stages of filling.

LNG will ultimately be consumed by a locomotive in vapor form. Southwest Research Institute investigated use of liquid injection, but found that extreme measures would be required to cool the liquid up to the injector tip (18). The liquid would flash boil upon injection, subjecting the injector tip to extreme thermal cycling. Such a system was not deemed technically feasible.

Given that vapor will be consumed, the fuel must be vaporized before reaching the locomotive engine. Vaporizing hardware is commercially available in the cryogenic industry. Ambient vaporizers are the first stage employed. These devices are heat exchangers, with the size of vaporizer depending on the rate of fluid flow and desired final temperature. Since the vapor leaves the heat exchanger possibly 50°F cooler than ambient temperature, a trim heater may be used to bring the gas up to higher temperature. Thermostatically controlled electric trim heaters are available.

An LNG tender could use a different vaporization system since engine heat is available. Engine cooling water would be an excellent source of heat. Another possibility is to cool the intake air with LNG, which is attractive for increasing knock-limited power output or reducing NOx emissions as discussed in Sections 4 and 5. Intake air cooling could be accomplished by using the intercoolers as heat exchangers for vaporization, or by allowing the engine to ingest cold methane vapor. It is not recommended that LNG be circulated through the intercoolers for safety reasons. A low temperature working fluid in a circulation loop must be used. Any use of engine heat to vaporize LNG will reduce the amount of heat rejected through radiators, allowing the possibility of reduced parasitic loads from cooling fans.

Consideration must be given to pumping vapor into the engine. The simplest approach is to build pressure inside the cryogenic tank which will drive the liquid and vapor through the lines. Pressure regulators will be needed to deliver the gas at a controlled pressure. Building tank pressure can be a slow process if no steps are taken other than closing the vent. Heat can be transferred into the tank to speed the process by drawing a liquid from the tank, passing it through a heat exchanger and returning it to the tank. Cryogenic tanks are supplied with a small heat exchanger for this purpose. Liquid flows due to convection; a pump is typically not used.

Cryogenic pumps deserve mention here. Such pumps are quite expensive and have low durability and reliability by engine standards. The reasons for such poor performance stems from the environment in which they must operate. No lubricants are available for such low temperatures; hence they run lubricated only by LNG. Sealing materials also face low temperature problems. If at all possible, a cryogenic pump should not be included in a locomotive system. Initial pump cost will be high, maintenance costs will be high, and reliability will be poor.

Once the fuel is vaporized and delivered to the locomotive under pressure, conventional dual-fuel engine hardware can be used to meter and handle the fuel.

The positioning of hardware onboard the locomotive and tender must be considered. The system must have provisions to disconnect the tender and locomotive easily. A fuel line will run between the tender and locomotive. The positioning of the vaporizers will determine whether this line contains liquid or vapor fuel. In this regard, it is desirable not to have liquid onboard the locomotive. If liquid were present in fuel lines on the locomotive when the engine is stopped or the tender decoupled, the liquid will vaporize, increasing pressure in the lines. The lines will then need to be vented. By contrast, if only vaporized fuel is onboard the locomotive, fuel lines can be decoupled safely with the vapor sealed in the lines at low pressure. Thus, positioning of the vaporizing hardware on the tender is attractive from a safety and handling standpoint.

The drawback to vaporizing LNG on the tender is that engine water or some working fluid must be pumped from the locomotive to the tender if engine heat is to be used. Two additional hoses with quick-connects will complicate locomotive and tender coupling, but only by a small measure.

Venting of a cryogenic tender is of concern for safety and fuel utilization. A number of situations must be considered, included wayside storage of unused tenders, train stops, locomotive idling, and powered operation. Each of these subjects is discussed below.

An unused tender or a tender that is not flowing fuel to a locomotive will have the greatest venting rate. This results from the fact that no liquid is being drawn from the tank and the ullage volume is essentially constant. By contrast, when liquid flows from a tank, the ullage volume increases, helping to reduce tank pressure. Vented fuel must not flow to an ignition source before it is diluted with air to a fuel/air ratio below the flammability limit. Unused tenders should be parked away from operating equipment and ignition sources, and in a well ventilated area. With vents fully open, the cars will remain at low pressure and require little attention. However, the cars will continuously loose fuel as vapor, which may be a costly proposition. Also, some time will be required to build tank pressure before a tender can be put back in service.

Stopped locomotives pose a more serious problem. A tender that has been is service and is pressurized will vent at a higher rate than an unused tender. A locomotives connected to the tender contains many possible ignition sources, including the exhaust stack, alternator/generator, traction motors, small electric motors and hot metal surfaces. The vented gasses must be kept from the locomotive as well as other wayside ignition sources. This is a difficult proposition since the tank vent must meet overhead and side clearance requirements for rail cars. Possible solutions to the problem are forced dilution of expelled gasses with air and consumption of the gasses by the locomotive engines. Forced dilution could be accomplished by using a fan or blower to mix a large volume of air with methane as it leaves the vent. The lean flammability limit could then be reached before the mixture leaves the vent or within a safe distance of the vent. Ingestion of the vented fuel by the engine is possible, but it may not be practical. The boil-off will probably be greater than the amount of fuel required to idle the engine or operated at very low power. The engine might have to be self loaded to consume all of the vented gas. Another alternative is to simply close the tank vent. This may be feasible for short periods of time. Tank pressure will build while the vent is closed, but this is acceptable as long as the tank pressure rating is not exceeded. The amount of time the vent can remain closed will depend on the initial tank pressure and fluid level.

Powered operation of a locomotive will place the tender in situations ranging from zero fuel flow to rated fuel flow. The rate of tank venting will vary as a result during train operation. There will be a position in the Notch schedule above which boil-off will no longer be adequate to fuel the engine. Liquid must then be drawn from the tender and vaporized. The ramifications are that the tank vent will be closed with heat being transferred into the tank to maintain tank pressure during high power operation. The Notch position above which the vent is closed will depend on the size and configuration of cryogenic tank used.

The safety and handling problems differ for low power versus high power operation because of the venting. At low power, the primary concern will be disposal of the vented gasses. A locomotive/tender configuration that is being considered by Bombardier uses one tender to fuel two locomotives with the tender located between the locomotives. Vented methane will flow over a locomotive in this arrangement. Design and positioning of the tender vent will be critical to minimize the amount of methane that comes into contact with following cars and to insure rapid dilution with air. Again, ingestion of boil-off by the engines is an alternative, but the amount of gas may be too great for the lowest notches. Nonetheless, it may be worth investigating ingestion of the gas at low notches simply as a means of disposal. The gas may not burn to a significant degree in the engine because of excess air, but there is little doubt that exhaust gas from the engine will not be ignited by an external source.

High power operation will not face the safety problems associated with vented methane. The vent will be closed and the operational problem will be one of transferring adequate heat into the tank to maintain gas pressure. It may be necessary to recirculate part of the vaporized methane to the tank to provide adequate heat input. This problem should be addressed by an experienced cryogenic system designer.

Tunnels deserve special consideration when dealing with an LNG fueled locomotive. The confined space in a tunnel will, in all probability, make venting of boil-off a safety hazard. If the locomotive is at high power with the tank vent closed, a tunnel can be crossed safely. Low power operation will present safety problems. The simplest and most effective remedy is to close the tank vents before entering the tunnel. Again, the tank will build pressure while the vents are closed, which is acceptable as long as rated tank pressure is not exceeded. The railroads should be consulted to determine the maximum amount of time required for a train to clear a tunnel. The feasibility of closing the vents can then be determined.

The final item to be mentioned concerning venting is the buoyancy of methane. Methane at room temperature is lighter than air and rises. As a result, safety precautions in closed buildings usually include roof or ceiling ventilation. Cold methane, by contrast, is heavier than air and settles. A liquid leak or cold vapor leak will settle unit the gas warms. Stationary cryogenic tank vents are usually positioned quite high and the vapors are heated rapidly by surrounding air. Height restrictions for rail cars could place the vent at a low enough level to be of concern. Leaks are of greater concern since the gas will settle around or below cars. Design engineers should be aware that vaporized LNG can settle until heated, and develop safety practices accordingly.

Since the LNG fuel system will run from tender to locomotive, provisions should be made for possible breaks, ruptures or leaks in lines. Methane detectors are commercially available and are recommended for covered areas of the locomotive. Hydraulic or pneumatic fuzes are also recommended. These fuzes are commonly used in the aviation industry in hydraulic systems. They are check valves that actuate if flow past the valve exceeds a predetermined rate. In the event of a line rupture or break, the fuze actuates, prevent loss of fluid.

Rail regulations concerning LNG tenders are uncertain and have not been tested. My understanding of the situation is that regulations prohibit placing cars containing volatile matter immediately behind a locomotive. However, these cars are stipulated as being freight, and no mention is made of a tender. Burlington Northern received approval to place the CNG tender and locomotive in revenue service. It would thus appear that regulatory obstacles can be overcome in the United States at least for CNG.

The above discussion highlights a number of problems that must be solved when developing an LNG tender and locomotive. There is a large gap in understanding of LNG systems from the rail equipment side, and a similar lack of understanding of locomotive systems and rail operations from the cryogenic industry side. It is recommended that researchers, engineers from railroads, Bombardier and the cryogenic industry meet early in the Phase II project with the objective of defining a viable LNG fueling system. Parties that could contribute to the meeting include:

Quentin Baker, WBE- dual fuel engines, LNG fuel systems
Jim Wakenell, SwRI - dual fuel engines and LNG systems
Glenn O'Neal, SwRI - dual fuel engines

Ralph Ashworth, SwRI - cryogenic hardware and tanks
Steve Ditmeyer, BN - gas fueled locomotive, regulations
Les Olson, BN - gas fueled locomotive, LNG systems

The engineers listed from Southwest Research converted and EMD engine to LNG operation. A cryogenic system was designed and installed during that project. Quentin Baker managed that project before leaving SwRI to work for Wilfred Baker Engineering. Burlington Northern will have valuable input since they have made an operational CNG locomotive and have looked into LNG conversions. Also, Steve Ditmeyer is a former Federal Railroad Administration employee and is very familiar with regulations that must be met or waived.

7. CONCLUSIONS

The following conclusions were reached as a result of this study.

1. The lean operating limit of a dual-fuel engine will occur at one of two thresholds: the limit for pilot diesel fuel ignition, and the lean flammability limit of the gaseous fuel. A throttled engine will be limited by pilot ignition, whereas an unthrottled engine will reach the lean flammability limit of the gaseous fuel first.

2. The lean flammability limit of an LNG fueled Bombardier 251 dual-fuel engine in stock configuration is expected to be at an equivalence ratio of 0.4. Modifying the engine to increase swirl, turbulence, intake air temperature or pilot quantity will extend the lean limit to as low as 0.3.

3. The lean limit for pilot diesel fuel ignition in a throttled dual-fuel engine could not be determined analytically. A large number of variables effect pilot ignition delay, including pilot timing, intake temperature and pressure, compression ratio, and gas quantity. Pilot ignition limits are best determined experimentally.

4. The lowest notch position that can be run in a dual-fuel mode without throttling intake air is Notch 4. Notch 3 is marginally below the lean gas limit. Incorporating techniques such as are described in conclusion number 2 may make unthrottled operation at Notch 3 possible. Alternatively, throttling can be employed to increase Notch 3 equivalence ratio to within flammability limits. Notches 2 and 1 are below limits for dual-fuel operation and should be run in normal diesel mode.

5. Hydrocarbon and carbon monoxide emissions from the dual-fuel engine will be several times higher than a conventional diesel engine at low power and will decrease as power output increases. NOx emissions will be very low near the lean limit, but will be considerably higher than a normal diesel engine at full power. Exhaust smoke will be less than half of conventional diesel levels at full power, and still lower below full power.

6. While there are a number of problems to be solved in the design of an LNG tender and fuel system, venting of boil-off fuel from the cryogenic tank will be the single greatest operating problem. Vented fuel must be safely diluted with air before reaching any ignition source. Tenders connected to moving locomotives and stopped locomotives must be studies as well as tenders that are disconnected and parked.

8. RECOMMENDATIONS

The lean limit for dual-fuel operation is affected by a large number of variables as is evident from literature. It is recommended that laboratory engine tests be performed to confirm the lean limit as predicted by this study and to document the thermal efficiency and hydrocarbon emissions at the lean limit. While the engine may operate without misfire at an equivalence ratio of 0.4 without throttling, thermal efficiency may be poor and corrective measures may be needed.

Experiments are also recommended to study the impact of intake air throttling on pilot diesel fuel ignition, and subsequent gaseous fuel ignition, in the event that throttling is considered for Notch 3 dual-fuel operation.

Cooling intake air with LNG is attractive because of potential benefits in reducing knock and NOx at full power, and in decreasing parasitic load from locomotive cooling fans. Estimation of the cooling capacity available from vaporization of LNG at Notch 8 is recommended. The amount by which intake air temperature will be reduced can then be determined and the benefits studied. It is further recommended that use of an increased compression ratio in conjunction with a cooled intake (at high power output) be investigated. The amount by which compression ratio can be increased should be determined experimentally. Cold starting and low power dual-fuel performance will improve if compression ratio can be increased.

Lastly, it is recommended that a meeting be held early in the Phase II project with the objective of developing a viable LNG fueling system. Definition of the fueling system will be very valuable throughout Phase II research, design and development efforts. Engine designers, mechanical engineers from railroads, and representatives from the cryogenic industry should be present. The subject of rail regulations that apply to fuel tenders and cryogenic equipment should be discussed.

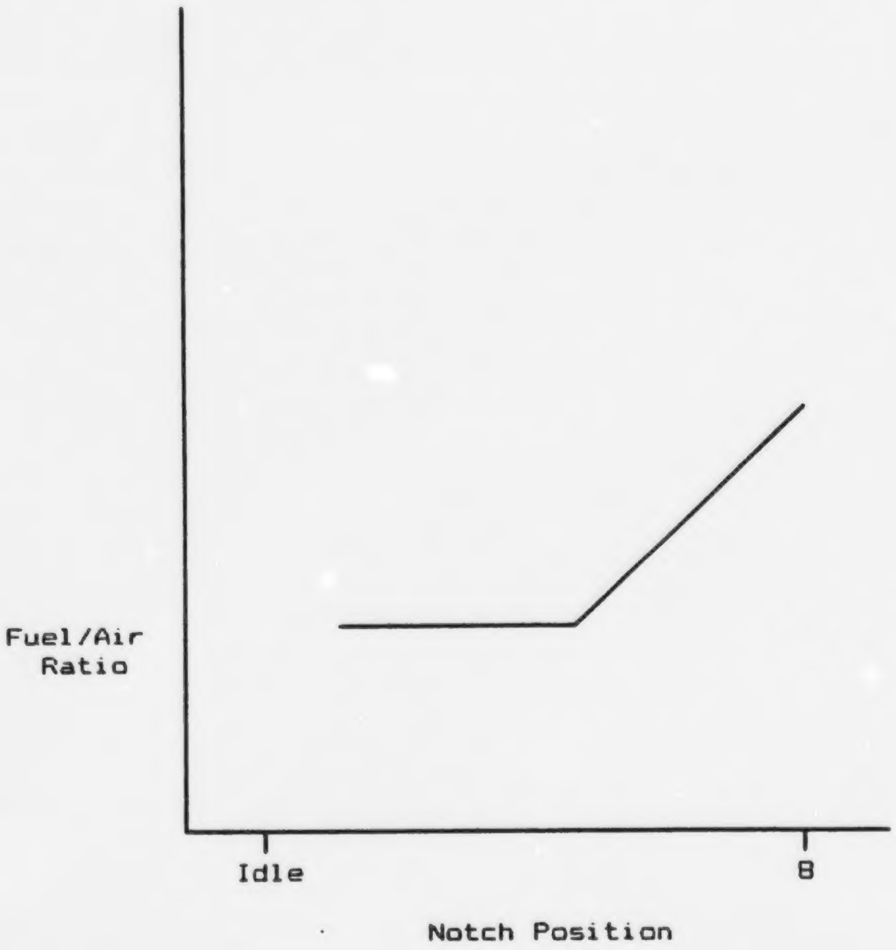

Figure 1
Expected Variation in Fuel/Air Ratio
of a Dual-Fuel Locomotive

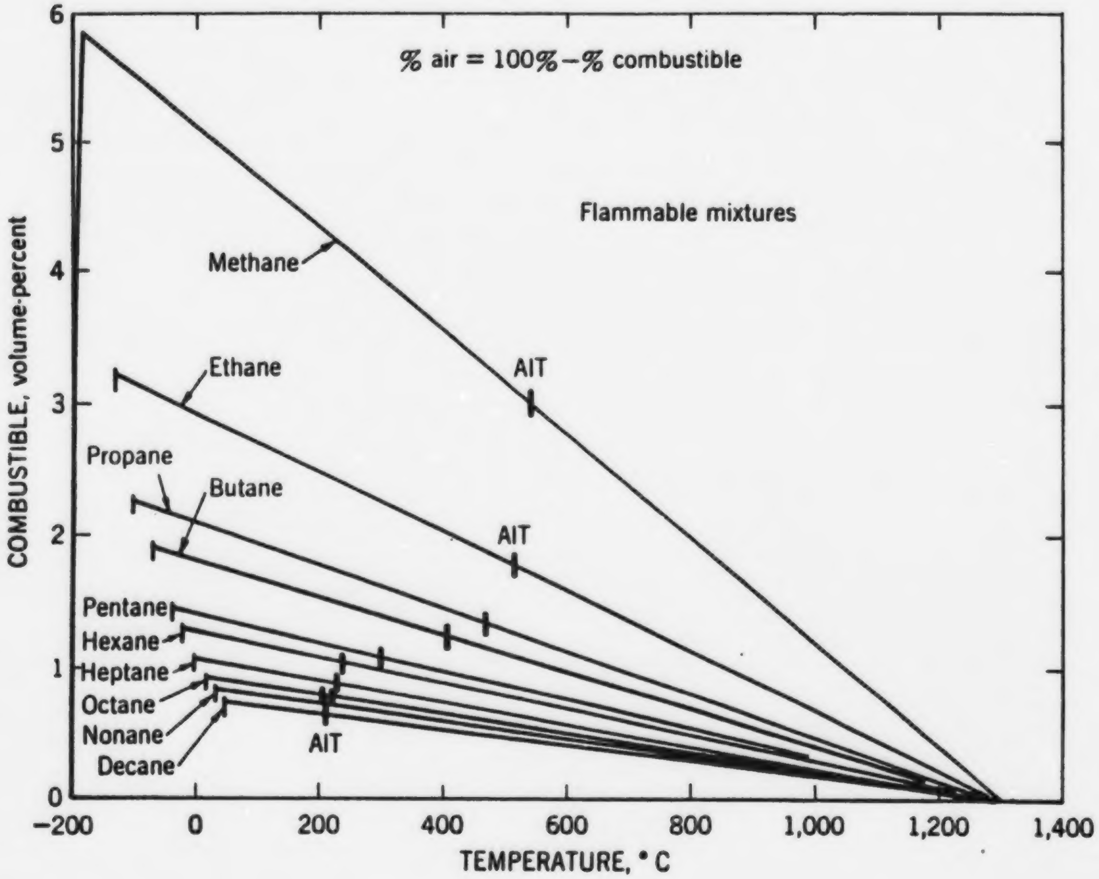

Figure 2
Effect of Temperature on Lower Limits of Flammability of 10 Paraffin Hydrocarbons in Air at Atmospheric Pressure (7)

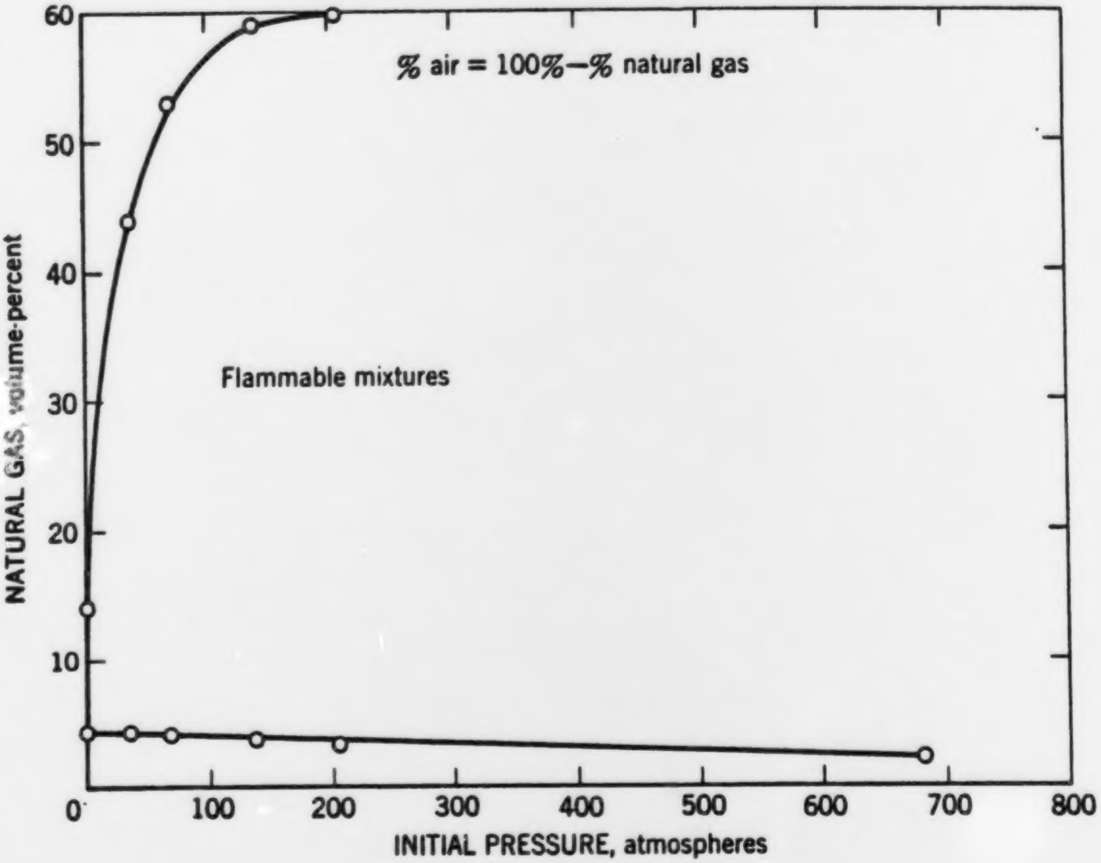

Figure 3
Effect of Pressure on Limits of Flammability of
Natural Gas in Air at 28°C (7)

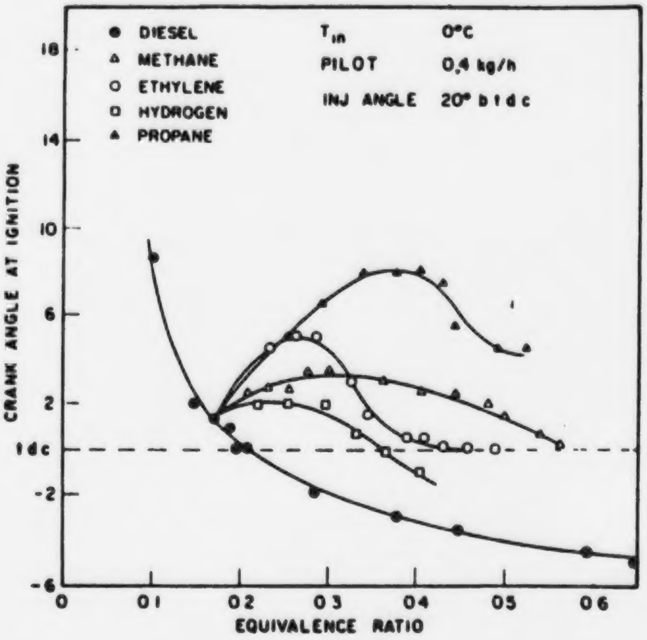

Figure 4
Ignition Delay of Pilot Diesel Fuel for an Intake Mixture at 0°C with Normal Diesel Operation Shown (5)

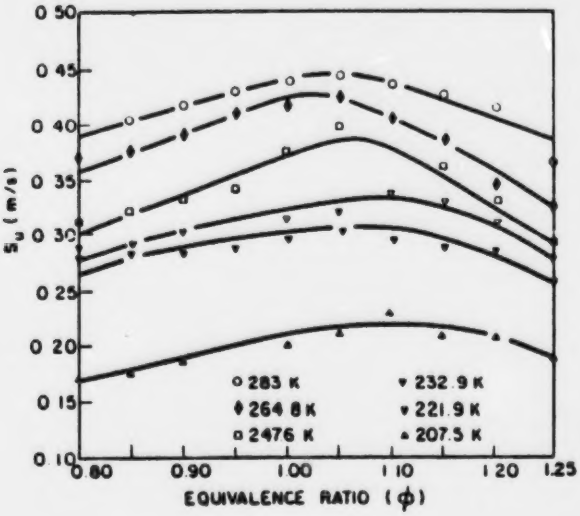

Figure 5
Variation in Burning Velocity as a Function of Equivalence Ratio and Mixture Temperatures in a Combustion Bomb (10)

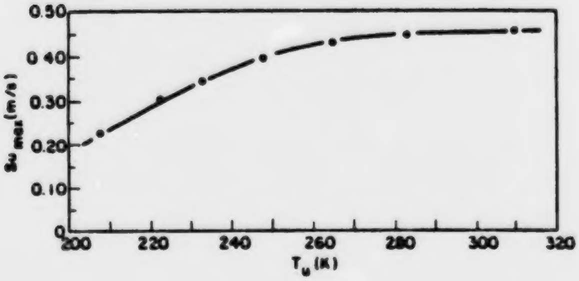

Figure 6
Variation in Peak Burning Velocity with
Mixture Temperature in a Combustion Bomb (10)

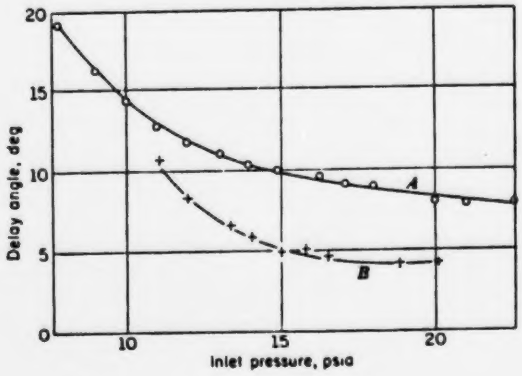

Figure 7
The Effect of Inlet Pressure on Pilot Ignition Delay (15)

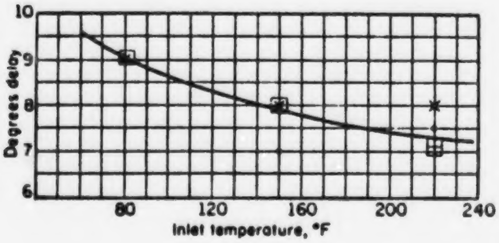

Figure 8
Effect of Inlet Temperature on Pilot Ignition Delay (15)

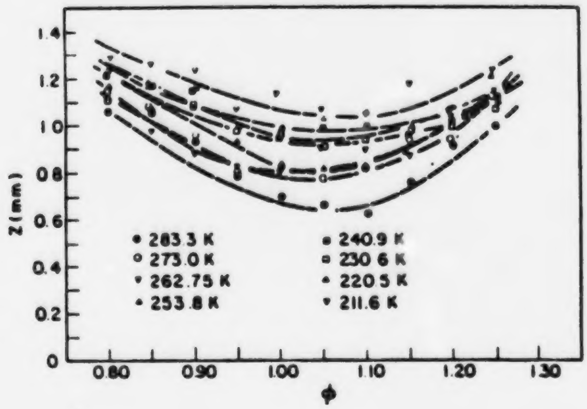

Figure 9
Variation in Quench Distance with Equivalence Ratio (10)

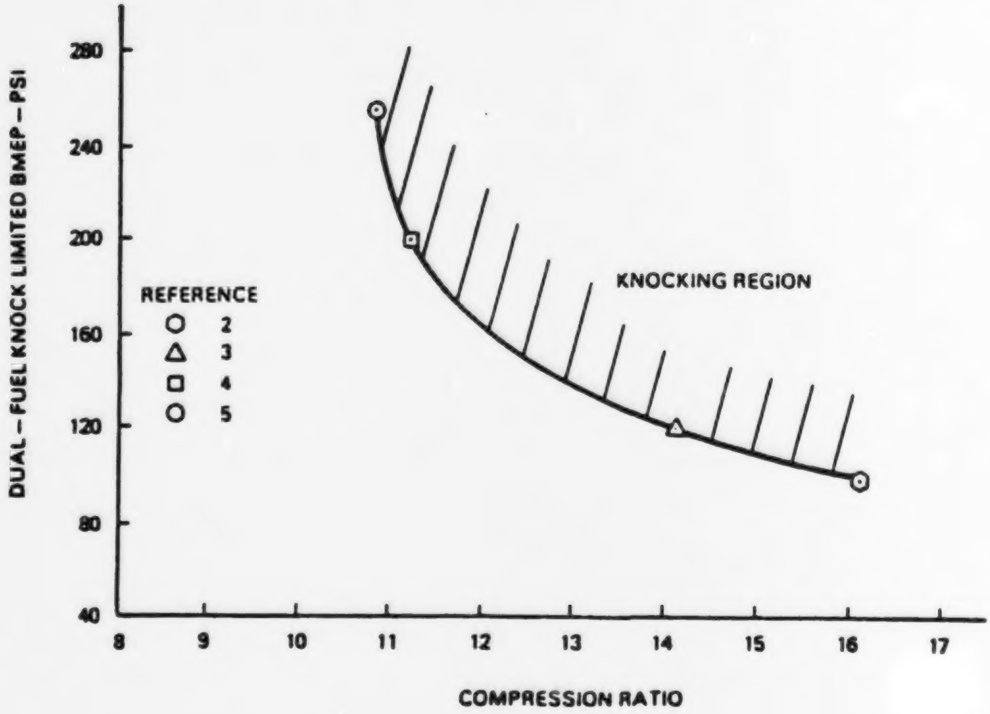

Figure 10
Compression Ratio Effects on Dual-Fuel
Knock Limited BMEP (4)

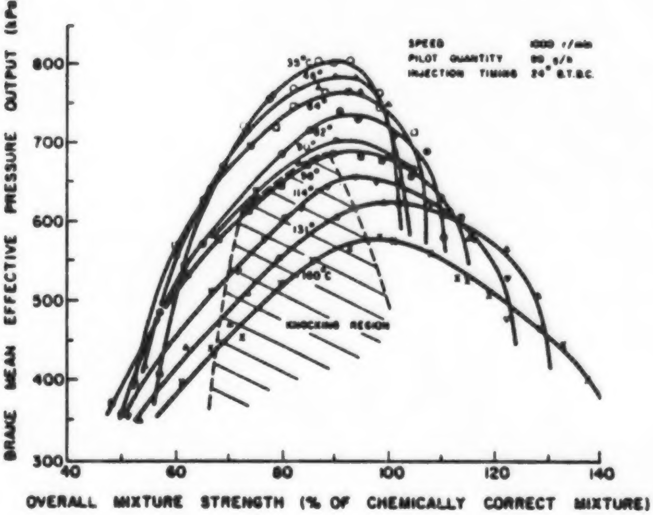

Figure 11
BMEP of a Dual-Fuel Engine Operated on Methane (5)

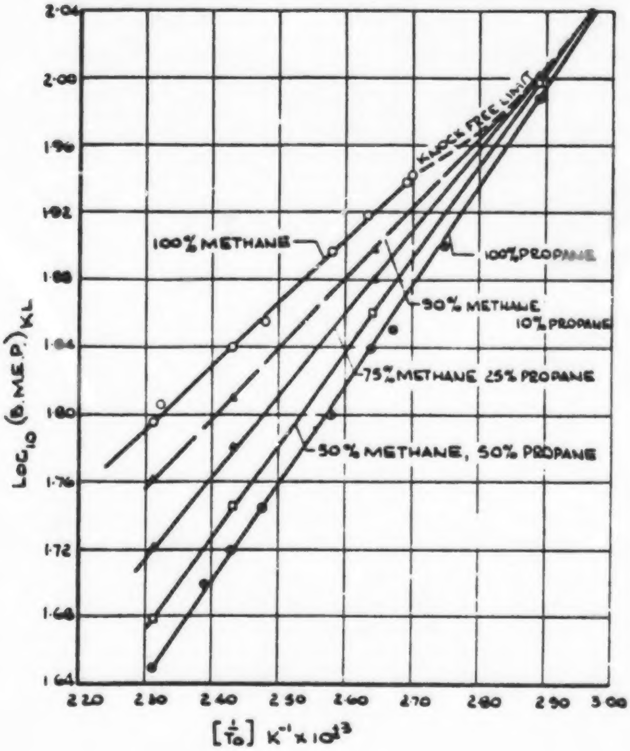

Figure 12
Correlation of the Knock Limited Output with Absolute Temperature of Intake Charge Using a Fixed Pilot Quantity and Intake Pressure (5)

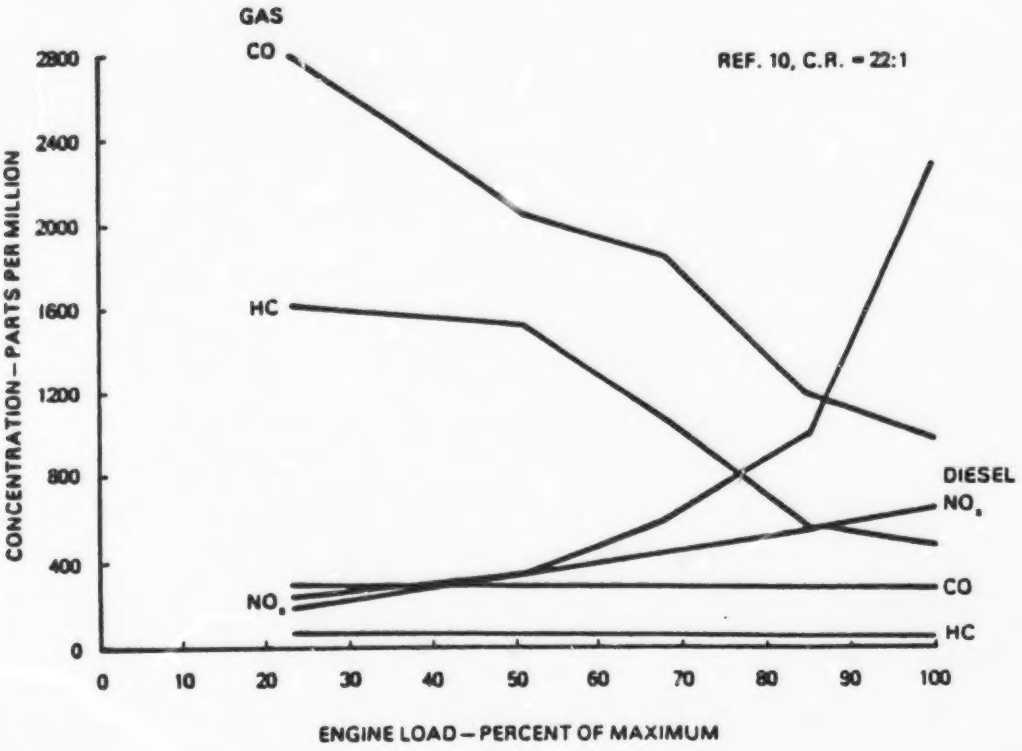

Figure 13
Dual-Fuel Engine Exhaust Emissions (4)

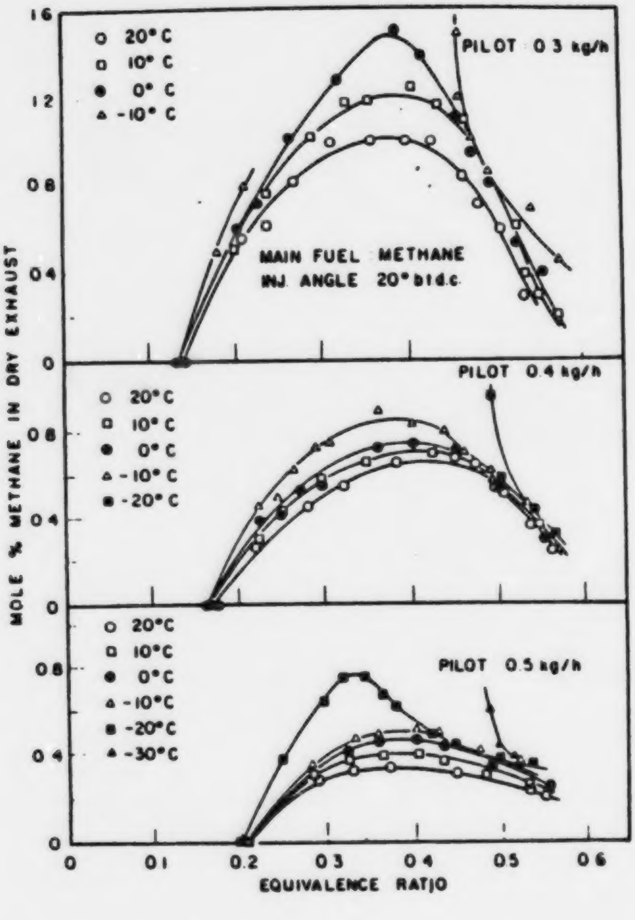

Figure 14
Methane Exhaust Concentration at Three Pilot Quantities (8)

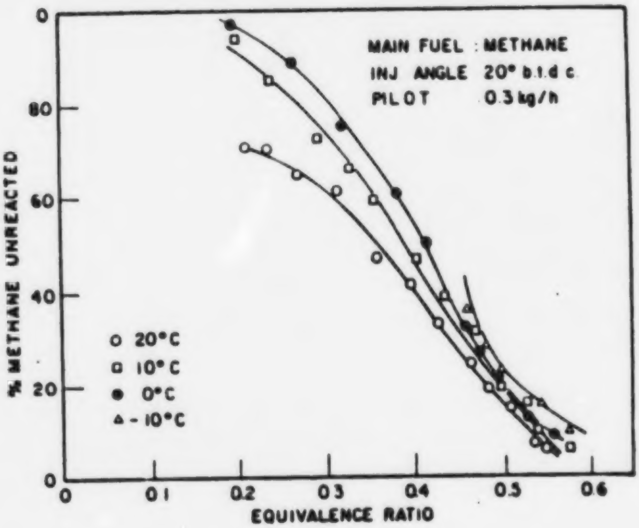

Figure 15
Unreacted Methane in the Exhaust of a Dual-Fuel Engine (8)

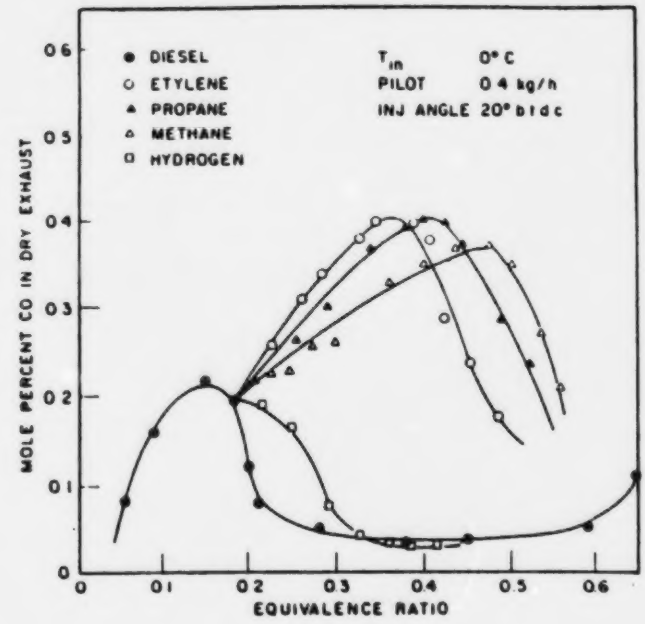

Figure 16
Carbon Monoxide Emissions from a Dual-Fuel Engine with Various Fuels Compared with Normal Diesel Operation (8)

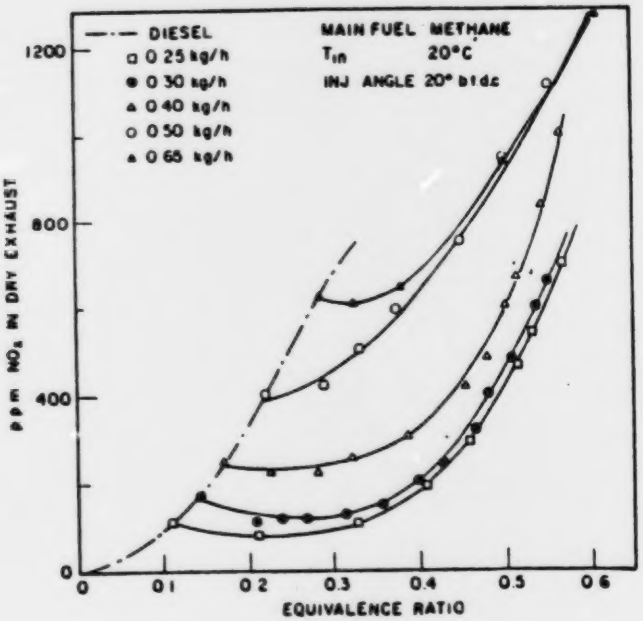

Figure 17
NOx Emissions from a Dual-Fuel Engine Using Methane (8)

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APPENDIX "C"

PHASE II WORK STATEMENT: - ENGINE CONVERSION (CURRENT TECHNOLOGY)

ENGINE CONVERSION
(Phase II)

DETAILED STATEMENT OF WORK

The following definition of the tasks and activities comprising Phase II of this project reflects the current technical and expertise of Bombardier Rail and Diesel Products Division. It differs, somewhat, in respect to the original scope of work in sequence and distribution of activities. This is due to the work accomplished (experienced) by RDPD over the past three years in the development of the 251 diesel engine burning natural gas. The tasks as outlined remain consistent with the overall objective of the program.

TASK I

This task consists ot the activities necessary to manage and control this Phase of work. Included is preparation of a detailed plan outlining the sequence of all activities in Gannt Chart or precedence form. Allowance will be made for the utilization of a computer generated network depending on the work breakdown complexity. Also included will be the preparation of a cash flow projection chart, monitoring of expenditures and monthly progress reports. In addition the attendance to meetings, conferences and consultants deemed necessary to stay abreast of current technology.

TASK II Design review (12-251 DF engine)

A conceptual design and functional specification were done as part of Phase I of this program the work itemized below is prerequisite to purchase of engine and control components

- Review and modify engine piping drawings.
- Modify standard engine overspeed control to suit, convert to electronic if feasible.
- Prepare manufacturing drawings of exhaust waste gate system to suit locomotive applicaticn.
- Define fuel injection system to suit selected pump size.
- Prepare detail drawings of dual electric actuator linkages.

TASK III TEST CELL PREPARATION/GAS SUPPLY

This task addresses,the establishing of a single cylinder 251-DF test facility.

The major activities are:

- Installation of a gas supply pipe line.
- Test cell modifications to handle natural gas including gas detectors and ventilation.
- Modification of 251 BSCRE to accept gas including 251-DF components.
- Commissioning of test cell.

TASK IV DIESEL ENGINE (251-12 cylinder)

A used 12 cylinder diesel engine will be refurbishsed to current standards then fitted with a new turbocharger system. This task covers all components and labor required in disassembling and rebuilding.

TASK V ENGINE CONVERSION

This task consists of procuring the gas conversion kit and fitting these items to the engine. Components within the kit are: -

- Dual-fuel control actuators (Woodward 3199)
- Electronic governor (Woodward 501)
- Dual-fuel gas admission valve assemblies
- Exhaust manifold and wastegate assembly
- Gas control valve (Woodward)
- Fuel injection equipment (Bryce)

TASK VI ENGINE TEST/OR OPTIMISATION

In this task the 12-251-DF engine will be tested to first establish a baseline over the standard locomotive notch speed range in the diesel mode. The performance parameters obtained will establish the limits for dual-fuel operation of the engine as built. The engine will then be optimised in the dual-fuel mode.

TASK VII DUAL-FUEL DEVELOPMENT (1-251 BSCRE-DF)

Based on previous studies of Bombardier and others pertaining to dual-fuel compression ignition engines, an extensive matrix of tests will be formatted. This work will be focused on the variable speed and load regime of a typical North American locomotive.

Some of this work will be readily transferable to the 12-251-DF while the greater portion will be for subsequent development phases. Those identified with an * will be part of this Phase.

* - Lowest notch (speed) for dual-fuel operation.
(standard equipment)
* - Minimum pilot fuel quantity (standard equipment)
- Air fuel ratio control
- Wastegate vs throttling
- Influence of intake air temperature
- Influence of compression ratio
- Influence of pilot fuel residence
* - Dual helix F.I. pumps
* - Optimum fixed pilot quantity
- Electronic gas admission valve
- Electronic fuel injector
- Knock sensing
- EGR

TASK VIII DOCUMENTATION AND REPORTS

The activities under this task will consist of: -

- A review and analysis of work performed
- The preparation of a descriptive report on the conversion of a 12-251-DF engine suitable for in-locomotive demonstration
- A status report of the 1-251 BSCRE-DF development work
- Recommendation for continuing the 1-251-BSCRE-DF development studies.

Revised 871204

LARGE DUAL-FUEL DIESEL
NATURAL GAS ENGINE DEVELOPMENT
PHASE II

(Engine conversion)

ESTIMATE COST:

TASK I:	PROJECT MANAGEMENT			
	ENGINEERING:	900 M/HRS	$ 34,263	
	TRAVEL:		10,000	
	MISC.:		3,000	
				$ 47,263
TASK II:	DESIGN REVIEW			
	ENGINEERING	300 M/HRS	12,000	
				12,000
TASK III:	TEST CELL/EQUIPMENT			
	ENGINEERING:	263 M/HRS	10,000	
	MATERIAL:		150,000	
	TRAVEL:		-	
	MISC.:		5,000	
				165,000
TASK IV:	DIESEL ENGINE			
	PURCHASE AND REFURBISH		250,000	
				250,000
TASK V:	ENGINE CONVERSION			
	ENGINEERING:	819 M/HRS	31,200	
	MATERIAL:		116,000	
				147,200

Revised 871204

LARGE DUAL-FUEL DIESEL
NATURAL GAS ENGINE DEVELOPMENT
PHASE II

(Engine conversion)

TASK VI: ENGINE TEST & OPTIMIZATION (12-251-DF)

ENGINEERING	394 M/HRS	$ 15,000	
MATERIAL/FUEL		25,000	
TRAVEL		3,000	
			$ 43,000

TASK VII: DUAL-FUEL DEVELOPMENT (1-251 BSCRE-DF)

ENGINEERING	408 M/HRS	15,537	
MATERIAL		10,000	
			$ 25,537

TASK VIII: DOCUMENTATION/REPORTS

ENGINEERING	200 M/HRS	8,000	
TRAVEL		-	
MISC.		2,000	
			10,000
	TOTAL:		$700,000

Revised 871204

LARGE DUAL-FUEL DIESEL

NATURAL GAS ENGINE DEVELOPMENT

PHASE II

COST BREAKDOWN

LABOR - ENGINEERING & LAB.	$126,000	
LABOR - SHOP	50,000	
MATERIAL	501,000	
TRAVEL EXPENSES	13,000	
MISC.	10,000	
		$700,000

MATERIAL BREAKDOWN

USED ENGINE	$100,000	
REBUILD KIT & MISC. ENGINE PARTS	24,000	
TURBO SUPPORT	7,000	
TURBOCHARGER	40,000	
GAS MANIFOLD & VALVE	10,000	
ELECTRONIC GOVERNOR	40,000	
EXHAUST MANIFOLD	15,000	
WASTEGATE	10,000	
F.I.E.	18,000	
FUEL	25,000	
NG PIPELINE	53,000	
SAFETY EQUIPMENT	31,000	
COMPRESSOR	67,000	
VALVE GEAR & AIR ELBOW	55,000	
CYLINDER HEAD COVERS	6,000	
		$501,000

Revised 871204

LARGE DUAL FUEL DIESEL
NATURAL GAS ENGINE
PHASE II
(Cost allocation)

TASK	PARTICIPANT	%	$ VALUE
I	TRANSPORT CANADA	100%	47,263
II	TRANSPORT CANADA	100%	12,000
III	TRANSPORT CANADA	70%	115,200
VII	TRANSPORT CANADA	100%	25,537
III	GMI	30%	50,000
IV	BOMBARDIER	100%	250,000
V	ONTARIO MEny	100%	147,000
VI	ONTARIO MEny	100%	43,000
VIII	ONTARIO MEny	100%	10,000
	TOTAL:		$700,000

PARTICIPANT	%
TRANSPORT CANADA	28
BOMBARDIER	36
ONTARIO MEny	28
GMI	8
	100